PHYSICAL REVIEW A VOLUME 41, NUMBER 11 1 JUNE 1990

Plasma shift and broadening of analogous transitions of S II, Cl III, Ar IV, Cl II, and Ar III

R. Kobilarov* and N. Konjević
Institute of Physics, P.O. Box 57, 11001 Belgrade, Yugoslavia

(Received 5 January 1990)

We report results of an experimental study of Stark broadening and shift of analogous transitions of S II, Cl III, Ar IV, Cl II, and Ar III in plasma of a low-pressure pulsed arc. These results, together with other available experimental data, were used for investigation of Stark broadening and shift of analogous transition of isoelectronic ions. Results of modified semiempirical calculations are used for comparison.

I. INTRODUCTION

Plasma broadening and shift of spectral lines for various elements and their positive ions have been studied extensively (see, e.g., Refs. 1–4). Wiese and Konjević[5] made an attempt to derive from the width measurements certain regularities and similarities which can be used as useful guides in further theoretical and experimental investigations and applications of width data in plasma diagnostics. Here we should emphasize that at the time of publication of Ref. 5, experimental data for the Stark widths along isoelectronic sequence were very scarce (see Table III in Ref. 5), so the authors[5] could only conclude that "the widths decrease strongly with increasing ionic charge." Recently, Böttcher *et al.*[6] have studied the dependence of the Stark broadening on the emitter charge Z for the $3s$-$3p$ transitions of Li-like ions. Their measurements clearly show a Z^{-1} dependence of the Stark width on the emitter ionization stage.

Although on the basis of atomic energy-level structure one can expect similar regularities for the Stark shifts because of the lack of experimental data, it was not possible to perform a similar type of analysis. For example, data for analogous transitions of homologous atoms and ions were almost completely lacking, while shift measurements along isoelectronic ions were completely missing. Recently, Purić *et al.*[7] have studied shifts of resonant transitions of alkali metals, while we have reported measurements of widths and shifts of analogous transitions of halogen atoms.[8]

In this paper we present experimental results for plasma shifts and widths of several spectral lines of singly ionized sulfur (S II) and chlorine (Cl II), doubly ionized chlorine (Cl III) and argon (Ar III), and triply ionized argon (Ar IV). These results together with other available data will be used both to test theoretical calculations and to demonstrate regularities of Stark shifts and widths of analogous transitions of isoelectronic ions.

II. THEORY

For evaluation of electron impact Stark widths and shifts of investigated ionic lines we used the so-called modified semiempirical (MSE) approach as proposed by Dimitrijević and Konjević[9] for widths, and by Dimitrijević and Kršlanin[10] for shifts. It is important to note here that for Stark width calculations[9] one requires data for several perturbing energy levels only, while for shift calculations[10] a complete set of perturbing levels is required. Furthermore, in some cases for an estimation of Stark width and shifts, simple formulas[11] for the low-temperature limit of MSE approach are also used.

III. EXPERIMENT

A. Plasma source and experimental procedure

Plasma sources and experimental procedure .are described elsewhere,[12,13] so only a few details will be given here.

A low-pressure pulsed arc is used as a plasma source. It consisted of a low-inductance discharge capacitor and the discharge tube. The pulsed arc is fired by an ignitron. (See Fig. 1 in Ref. 13.) Since it was necessary to excite spectral lines of different ionization stages and to measure in some cases exceedingly small widths and shifts, we used two capacitor banks: one with 10 μF and another with 5 μF (see Table I). In all experiments the charging voltage of capacitor banks was constant, 14 kV, and the period of the ringing frequency of the whole circuit including discharge was, with both capacitor banks, 12.5 μs. This was achieved by changing the diameter of one of the discharge tubes until the impedance of the whole circuit became equal to the discharge of another capacitor bank. The diameter of a larger discharge tube used with 10 μF was 31 mm, while the narrower one, 13.5 mm diameter, was used with 5-μF capacitor (see Table I), both tubes being made of Pyrex glass. The distance between the end aluminum electrodes in both cases was 28 cm.

Measurements of spectral line shapes and shifts were preceded by careful selection of the gas mixtures when gases with investigated elements were gradually diluted until optically thin conditions for the desired lines were reached. This was checked by comparing line intensity ratios within multiplets with those expected from LS coupling (see, e.g., Ref. 2). A detailed study of the possible influence of self-absorption on the line shapes were performed by use of an auxiliary electrode (see Fig. 1, in Ref. 13). This electrode, located between end electrodes, is made of aluminum also, but with a thin surrounding

TABLE I. Experimental conditions and plasma diagnostics used for determination of electron density and temperature.

Ion	Transition	Capacitor bank (μF)	Internal diameter of the discharge tube (mm)	Gas mixture (vol %)	Plasma diagnostics		
					electron density	electron temperature	
S II	$4s\,{}^4P$–$4p\,{}^4D^0$	5	13.5	10%SF_6–90% He	He-Ne laser interferometer at 6328 Å	O II	4366.9 Å 4369.3 Å
Cl II	$4s'\,{}^3D^0$–$4p'\,{}^3P$	5	13.5	5% CCl_2F_2–95%He	He-Ne laser interferometer at 6328 Å	O II	4366.9 Å 4369.3 Å
Cl III	$4s\,{}^4P$–$4p\,{}^4D^0$ $4s'\,{}^2D$–$4p'\,{}^2F^0$	5	13.5	5% CCl_2F_2–95% He	He-Ne laser	O II	4366.9 Å
					interferometer at 6328 Å		4369.3 Å
Ar III	$4s\,{}^3S^0$–$4p\,{}^3P$ $4s'\,{}^3D^0$–$4p'\,{}^3P$ $4s'\,{}^3D^0$–$4p'\,{}^3D$	10	31.0	3.5% Ar–96.5% He	Stark width of He II 4686 Å	O III	3754.2 Å 3707.2 Å 3702.7 Å 3455.1 Å
Ar IV	$4s\,{}^4P$–$4p\,{}^4D^0$ $4s'\,{}^2D$–$4p'\,{}^2F^0$	10	31.0	3.5% Ar–96.5% He	Stark width of He II 4686 Å	O III	3754.2 Å 3707.2 Å 3702.7 Å 3455.1 Å

ring.[13] The iron ring is used to move the electrode from the outside by means of a magnet. In this way it is possible to vary plasma length and accordingly the absorption conditions of plasma layer under investigation without changing the electrical impedance of the circuit, i.e., plasma conditions remain unchanged.

Holes, 1.8 mm diameter, are located at the center of all three electrodes to facilitate optical alignment and to perform laser interferometric measurements of electron density. The hole in the auxiliary electrode was blocked by a cutoff filter transparent for the wavelengths larger than 6000 Å only. During the experiment a continuous flow of selected gas mixtures (see Table I) is maintained at a pressure of 133 Pa (1 torr).

The light from a pulsed arc is observed end-on on a shot-to-shot basis with a 1-m monochromator (inverse linear dispersion 4.2 Å/mm) equipped with photomultiplier tube. This instrument has with 12 μm slits a measured instrumental half-width of 0.06 Å. The discharge is imaged onto the entrance slit of the monochromator by means of a concave mirror, see Fig. 1 in Ref. 13. The diaphragm placed in front of the concave mirror ensures that the light comes only from the central, 1.5 mm diameter of the plasma about the arc axis.

The contribution of instrumental and Doppler broadening to the width of measured ionic lines was not negligible under our experimental conditions. Therefore to obtain a Stark profile from the measured one it was necessary to use a deconvolution procedure for Gaussian (instrumental and Doppler) and dispersion (Stark) profile.[14]

From line-shift measurements we used plasma radiation at the late times of plasma decay as a source of less shifted line profiles.[12,13,15] Thus to measure the line shift it is necessary to analyze oscilloscope traces obtained from the photomultiplier-monochromator system at various wavelengths and at various times of the decay. Here one should notice that the reported shifts are measured at the half-width of both line profiles. Furthermore, all fittings of experimental points at the line profile were performed with the aid of a computer.

B. Plasma diagnostics

For axial electron-density measurement we used a single wavelength 6328 Å laser interferometer with a plane external mirror[16] or Stark width of He II Pashen-α, 4685.7-Å line (see Table I). The full width at half maximum $\Delta\lambda_{\mathrm{FWHM}}$ of a 4685.7-Å line is related to the electron density N_e using the following relationship:[17–20]

$$N_e = 2.04\times10^{16}(\Delta\lambda_{\mathrm{FWHM}})^{1.21}\ \mathrm{cm}^{-3}\ .$$

The axial electron temperature is determined from the Boltzmann plot of O III 3754.21-, 3707.24-, 3702.75-, and 3455.12-Å or from relative intensities of O II 4366.90-, and 4369.31-Å impurity lines (see Table I) with transition probabilities being taken from Wiese *et al.*[21] To determine electron temperature, thermal equilibrium in an optically thin medium is assumed. The spectral response of the photomultiplier-monochromator system is calibrated against a standard tungsten coiled-coil quartz-iodine lamp.

IV. EXPERIMENTAL RESULTS AND DISCUSSION

Experimental results for Stark widths w_m and Stark shifts d_m of Cl II and Ar III lines are given in Table II, while the results for S II, Cl III, and Ar IV lines are in Table III. Tables II and III contain spectroscopic data for the investigated lines, plasma parameters T_e and N_e, at which w_m and d_m are measured. The estimated error

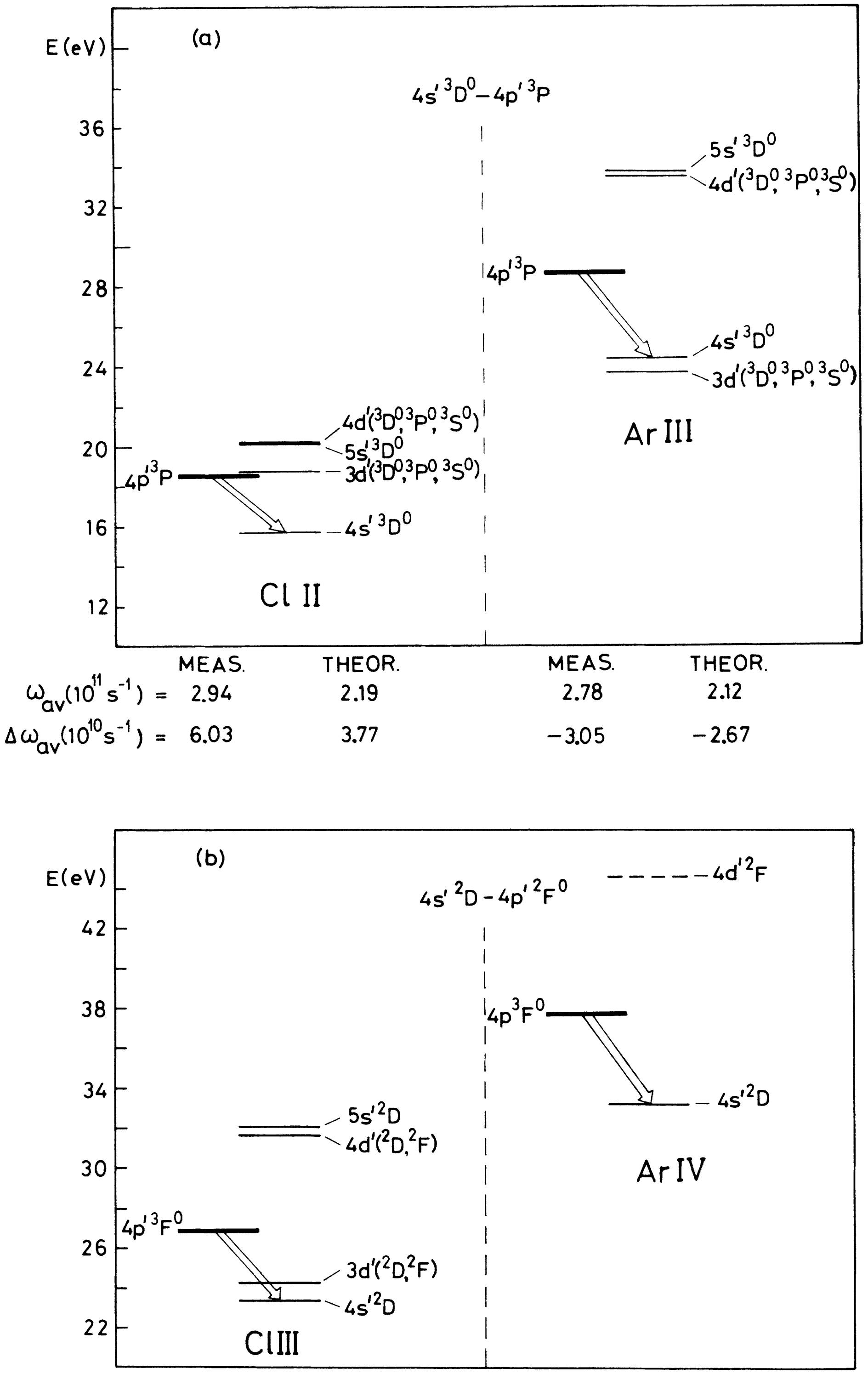
TABLE II. Experimental electron impact full widths w_m and shifts d_m of investigated Cl II and Ar III lines. Experimental results are compared with theoretical widths w_{MSE} and shifts d_{MSE} calculated using a modified semiempirical approach (Refs. 9 and 10).

Ion	Transition	λ (Å)	T_e(K)	N_e (10^{17} cm^{-3})	w_m (Å)	d_m (Å)	$\frac{w_m}{w_{\mathrm{MSE}}}$	$\frac{d_m}{d_{\mathrm{MSE}}}$
Cl II	$4s'\,^3D^0$–$4p'\,^3P$	4336.3	31 000	1.4	0.41 ± 0.03	$0.03\pm0.00_8$	1.34	1.59
			27 000	0.9	0.28 ± 0.02		1.33	
		4343.6	31 000	1.4	0.42 ± 0.03	$0.03\pm0.00_8$	1.37	1.59
			27 000	0.9	0.28 ± 0.02		1.33	
Ar III	$4s'\,^3D^0$–$4p'\,^3P$	2855.3	110 000	10.0	0.62 ± 0.05	$-0.03\pm0.00_8$	1.16	1.16
			80 000	5.8	0.44 ± 0.04		1.27	
		2884.1	110 000	10.0	0.66 ± 0.05	$-0.03\pm0.00_8$	1.21	1.14
			80 000	5.8	0.45 ± 0.04		1.28	
	$4s'\,^3D^0$–$4p'\,^3D$	3499.7	110 000	10.0	0.78 ± 0.06	-0.05 ± 0.01	0.98	1.04
			80 000	5.8	0.53 ± 0.05		1.04	
		3503.6	110 000	10.0	0.78 ± 0.06	-0.04 ± 0.01	0.98	0.83
			80 000	5.8	0.54 ± 0.05		1.06	
	$4s\,^3S^0$–$4p\,^3P$	3511.1	110 000	10.0	0.90 ± 0.06	-0.06 ± 0.01	1.05	0.99
			80 000	5.8	0.60 ± 0.05		1.09	
		3514.2	110 000	10.0	0.94 ± 0.06	-0.06 ± 0.01	1.09	0.99
			80 000	5.8	0.64 ± 0.05		1.16	

in N_e measurements is ±10% whenever laser interferometer is used (see Table I). Electron density determined from the He II P_α line is uncertain within ±11%. Electron temperatures derived from the ratio of O II line intensities are accurate within ±15%, while those determined from the Boltzmann plot of O III lines, see Table I, have the estimated uncertainty of ±10%. The estimated error in Stark width and shift measurements are given in Tables II and III. In the last two columns of Tables II and III, comparison with theoretical results is given. For the evaluation of theoretical Stark widths and shifts using the MSE approach[9,10] all necessary atomic data are taken from Refs. 22 and 23. In addition, data for Ar IV $3d\,^4D$ and $3d\,^4F$ levels are taken from Ref. 24. Since data for Ar IV $4d$ and $4d'$ levels are missing in the literature, we estimated these levels from the disposition of energy levels along the isoelectronic sequence .[see Figs. 1(b) and 1(c)]. The results are given in Table IV.

TABLE III. Same as in Table II but for Si II, Cl III, and Ar IV lines.

Ion	Transition	λ (Å)	T_e (K)	N_e (10^{17} cm^{-3})	w_m (Å)	d_m (Å)	$\frac{w_m}{w_{\mathrm{MSE}}}$	$\frac{d_m}{d_{\mathrm{MSE}}}$
S II	$4s\,^4P$–$4P\,^4D^0$	5453.8	32 600	1.1	0.46 ± 0.04	-0.04 ± 0.01	1.07	1.55
			28 500	0.7	0.31 ± 0.03		1.06	
		5473.6	32 600	1.1	0.46 ± 0.04	-0.04 ± 0.01	1.07	1.54
			28 500	0.7	0.31 ± 0.03		1.06	
Cl III	$4s\,^4P$–$4p\,^4D^0$	3656.9	31 000	1.4	0.26 ± 0.03	$-0.02\pm0.00_5$	1.10	1.97
			27 000	0.9	0.18 ± 0.03		1.11	
		3670.3	31 000	1.4	0.26 ± 0.03	$-0.02\pm0.00_5$	1.10	1.96
			27 000	0.9	0.18 ± 0.03		1.10	
		3705.5	31 000	1.4	0.24 ± 0.03	$-0.02\pm0.00_5$	0.99	1.92
			27 000	0.9	0.16 ± 0.03		0.96	
	$4s'\,^2D$–$4p'\,^2F^0$	3530.0	31 000	1.4	0.27 ± 0.03	$-0.02\pm0.00_5$	1.21	1.38
			27 000	0.9	0.18 ± 0.03		1.17	
		3560.7	31 000	1.4	0.26 ± 0.03	$-0.02\pm0.00_5$	1.16	1.38
			27 000	0.9	0.18 ± 0.03		1.17	
Ar IV	$4s\,^4P$–$4p\,^4D^0$	2788.9	110 000	10.0	0.49 ± 0.05	$-0.03\pm0.00_8$	1.05	1.04
			80 000	5.8	0.34 ± 0.04		1.11	
		2809.4	110 000	10.0	0.48 ± 0.05	$-0.03\pm0.00_8$	1.01	1.03
			80 000	5.8	0.32 ± 0.04		1.03	
		2830.3	110 000	10.0	0.51 ± 0.05	$-0.03\pm0.00_8$	1.06	1.01
			80 000	5.8	0.34 ± 0.04		1.08	
	$4s'\,^2D$–$4p'\,^2F^0$	2757.9	110 000	10.0	0.52 ± 0.05	$-0.03\pm0.00_8$	1.19	1.04
			80 000	5.8	0.35 ± 0.04		1.18	



	MEAS.	THEOR.	MEAS.	THEOR.
$\omega_{av}(10^{11}\,s^{-1})$ =	2.94	2.19	2.78	2.12
$\Delta\omega_{av}(10^{10}\,s^{-1})$ =	6.03	3.77	−3.05	−2.67

	MEAS.	THEOR.	MEAS.	THEOR.
$\omega_{av}(10^{11}\,s^{-1})$=	2.81	2.37	2.41	2.04 (1.61)
$\Delta\omega_{av}(10^{10}\,s^{-1})$=	−5.99	−4.30	−3.28	−3.18 (−6.93)

FIG. 1. Energy levels of the investigated transitions and relevant perturbing levels. Below each set of energy-level diagrams average experimental and theoretical results for widths ω and shift $\Delta\omega$ in frequency units (s^{-1}) are given. These results are normalized to $N_e=1\times10^{17}$ cm^{-3} and $T_e=31\,000$ K. Theoretical Ar IV data given in parentheses in (b) and (c) are the results obtained without (b) $4d'$ and (c) $4d$ levels. Energy-level data in this figure are taken from Refs. 22, 24, and Table IV.

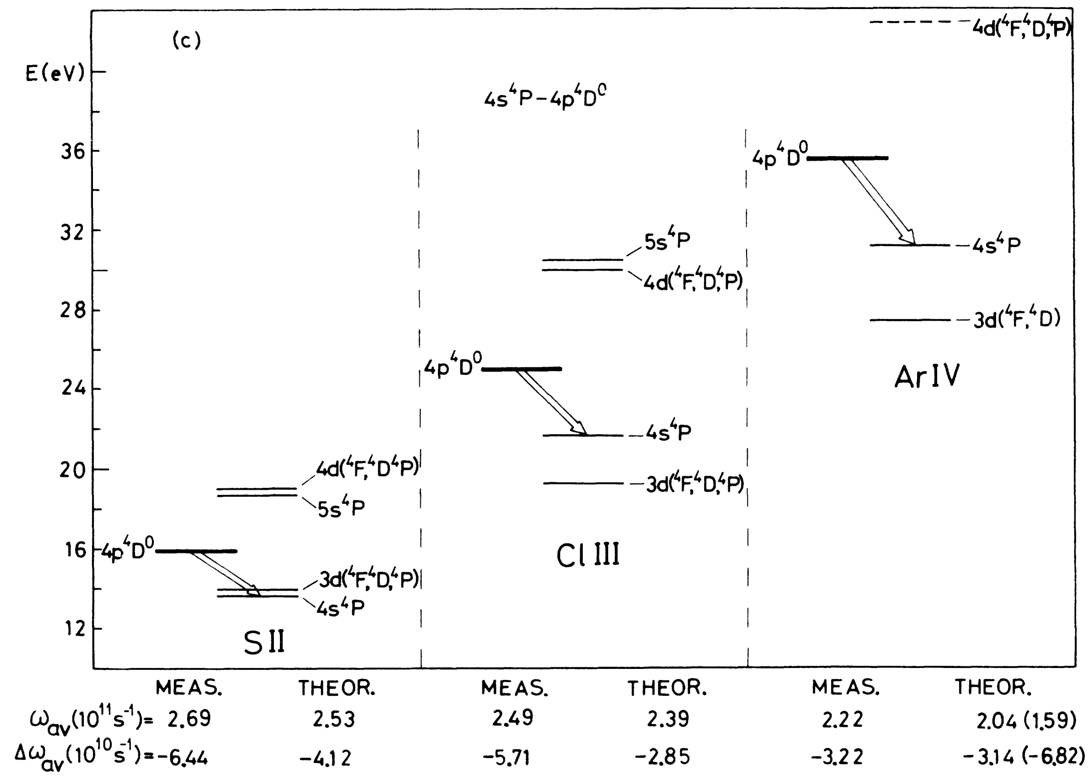


FIG. 1. (*Continued*).

The agreement between experimental and theoretical widths in Tables II and III is within 30%, this being well within the estimated uncertainty of the theory.[9] However, it is important to notice that theoretical widths are systematically smaller than the experimental values. In the case of shifts the discrepancy between experiment and theory[10] is larger and it varies from multiplet to multiplet. Here we draw attention to the importance of the completeness of the set of perturbing levels used in calculations of both width and shifts. This is well illustrated by the results for Ar IV multiplets [see data in Figs. 1(b) and 1(c)]. The introduction of $4d'$ [see Fig. 1(b)] and $4d$ [see Fig. 1(c)] in calculations considerably improves the agreement between theory and experiment. From these results it is also clear that shift calculations are more sensitive to the lack of perturbing levels.

In order to compare our results with other experiments we have to normalize all data to the same electron density N_e and electron temperature T_e. Linear dependence of the Stark width w_e and Stark shift d_e of spectral lines of isolated nonhydrogenic ions upon electron density has been checked and proved in a number of experiments (see, e.g., Refs. 2, 4, and 25). Therefore, scaling of experimental results to the same electron density $N_e=1\times10^{17}$ cm^{-3} should not introduce large uncertainty into the comparison. However, reliable investigations of $w_e(T_e)$ and $d_e(T_e)$ dependence in a large temperature range are almost completely missing. So for comparison we used the $w_e \sim 1/\sqrt{T_e}$ and $d_e \sim 1/\sqrt{T_e}$ dependence as predicted by MSE.[9–11] This scaling of experimental data from the wide temperature range to the same electron temperature introduces into the comparison large uncertainty which is very difficult to estimate. However, it is important to notice that the temperature at which scaling of experimental data is performed is selected in such a way that it is in the range of temperatures when $3kT/2\Delta E \geq 2$, where ΔE is the separation between upper (or lower) levels of the transition considered and nearest perturbing level. This is the region where, in accordance with the theory,[9–11] w_e and d_e are inversely proportional to the square root of temperature.

TABLE IV. Estimated energy levels of Ar IV.

Config.	Desig.	Energy level for multiplet (eV)
$3s^23p^2(^3P)4d$	$4d\,^4F$	42.07
$3s^23p^2(^3P)4d$	$4d\,^4P$	42.34
$3s^23p^2(^3P)4d$	$4d\,^4D$	42.36
$3s^23p^2(^1D)4d$	$4d'\,^2F$	44.31

In Fig. 2 our experimental results (in frequency units) for the widths and shifts of $4s\,^4P-4p\,^4D^\circ$ transitions of S II, Cl II and Ar IV are given normalized to $N_e=1\times10^{17}$ cm^{-3} and $T_e=31\,000$ K together with the results for widths of other authors[26–31] scaled to the same experimental conditions. For comparison two sets of theoretical results for widths and shifts are also given in Fig. 2. In the first case Ar IV widths and shifts are calculated

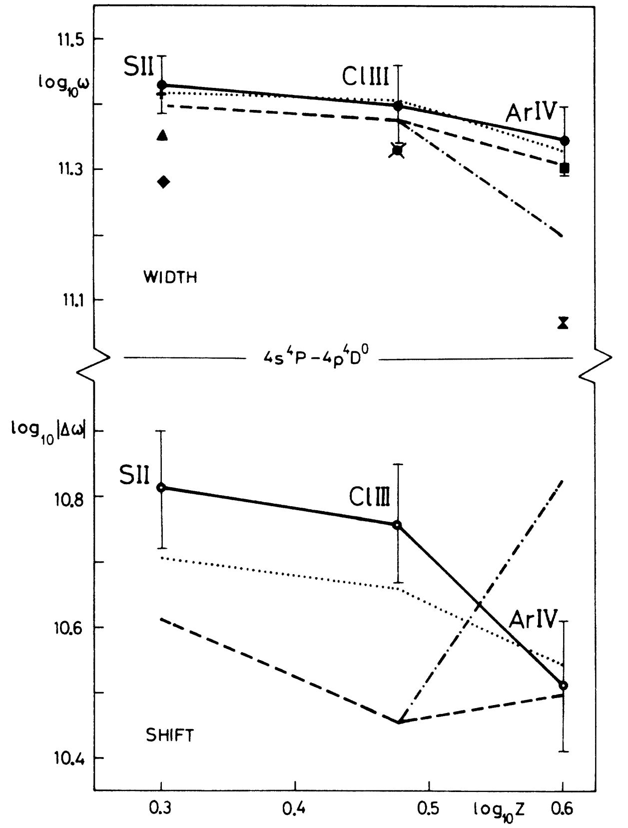


FIG. 2. Dependence of Stark width ω and shift $\Delta\omega$ (in frequency units) for the lines of $4s\,{}^4P$–$4p\,{}^4D^0$ transitions upon effective nuclear charge Z of ion. Experimental results as follows: ▲, Ref. 26; +, Ref. 27; ◆, Ref. 28; ⧓, Ref. 29; ⧗, Ref. 30; ■, Ref. 31; ● and ○ present results for widths and shifts, respectively. Theory: — — —, MSE (Refs. 9 and 10) with all energy levels presented in Fig. 1(c); —·—·— MSE (Refs. 9 and 10) without perturbing level $4d$ for Ar IV; · · · · low-temperature limit of MSE (Ref. 11). All data in this figure are for $N_e = 1\times10^{17}$ cm^{-3} and $T_e = 31\,000$ K.

from MSE (Refs. 9 and 10) without $3d$ perturbing level [see Fig. 1(c)] and with this level included. A second set of theoretical results is evaluated from simple formulas derived in Ref. 11 for the low-temperature limit of MSE.[9–10] These calculations do not require the knowledge of data for perturbing levels except through the $3kT/2\Delta E \leq 2$ condition which has to be satisfied.

Comparison of experimental widths in Fig. 2 show the following.

With the exception of data by Mar *et al.*,[28] all other results for S II agree with the present experiment within the limits of estimated errors.

For Cl III and Ar IV the present results agree well with those from Refs. 29 and 31; the discrepancy is rather large in the case of results from Ref. 30.

We believe that in Ref. 30 the measured temperature is too low (Ar IV linewidths are measured at 21 000–22 000 K), so when scaling $w_e \sim 1/\sqrt{T_e}$ is applied, a low value in Fig. 2 is obtained. Since all experimental data, with the exception of Refs. 28 and 30, are in reasonable agreement with the present experiment, we used only our experimental data for the derivation of the width dependence upon ion emitter charge Z.

Theoretical widths derived from MSE (Ref. 9) agree well with the present experimental results. The importance of the $4d$ level [see Fig. 1(c)] in calculation of Ar IV Stark widths is clearly illustrated. Further, the results obtained from low-temperature limit formula of MSE (Ref. 11) are in good agreement with experiment in spite of the fact that minimum atomic data are needed for calculations. This is of particular importance for the lines of multiply ionized atoms since the energy-level data are frequently missing.

In the case of Stark shifts, see Fig. 2, the lack of the $4d$ level leads to the change of the trend of theoretical shifts along isoelectronic ions. By taking into account the estimated value of $4d$ level (see Table IV), the agreement between theory[10] and experiment becomes excellent (see also Table III). This agreement is accidental, of course, since a number of perturbing levels (which are missing in literature) has to be taken into account. The low-temperature limit of MSE,[11] however, gives reasonable agreement with experiment, see Fig. 2.

For the Stark shifts in Fig. 2 there are no other experimental data available, and therefore only the comparison with theory[10,11] is performed. The analysis of experimental results shows a gradual decrease of both width and

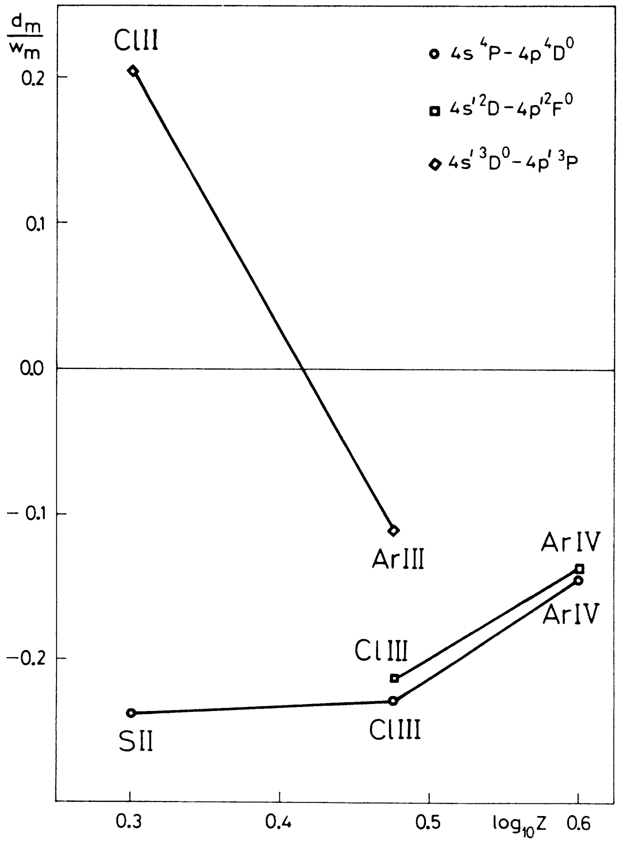


FIG. 3. Shift to width ratio of experimental data from Tables II and III.

shifts along isoelectronic sequence of ions, see data in Figs. 1(a)–1(c) and 2. In Fig. 3 the ratio of d_m/w_m shows the same behavior along the isoelectronic sequence, indicating that shifts decrease faster with Z.

It is interesting to notice the change of the sign of the shift for the $4s'\,{}^3D^0$–$4p'\,{}^3P$ transition from Cl II to Ar III, see Figs. 1(a) and 3. This can be easily understood from the disposition of relevant perturbing levels, see Fig. 1(a). In the case of Cl II the $3d'$ perturbing level is very close above the upper energy level of $4s'\,{}^3D^0$–$4p'\,{}^3P$ transition, while in Ar III the $3d'$ level is below the upper level adding up its influence to the perturbation induced by the $4s'$ level. As expected, with a reasonably complete set of perturbing levels, the theory[10] predicts correctly the sign of the shift in this case, see Fig. 1(a).

Gradual decrease of widths and shifts with the increase of emitter charge (along isoelectronic sequence) can be understood from energy-level diagrams, see examples in Fig. 1. Energy levels gradually spread along the sequence, so their influence as perturbers decreases, and as a consequence, electron impact widths and shifts become smaller. Obviously the rate of change of widths and shifts for a certain transition along the sequence depends upon the change of disposition of energy levels and it varies from transition to transition. This is well illustrated by examples in Figs. 2 and 4. In Fig. 4 we present the available experimental results for all cases when we could find results for the widths of analogous transition for at least three ions along isoelectronic sequence.[6,27,32–36] Unfortunately, there is a lack of reliable experimental data for shifts, so the only existing results are presented in Fig. 2. Together with experimental data in Fig. 4, theoretical results calculated using MSE (Ref. 9) are also presented. In order to derive width dependence upon effective ionic charge Z, a best fit straight line is drawn through data points whenever they show smooth gradual change with Z. The results are given in Table V. Due to the large scatter of experimental data, the best fit line through data points in Figs. 4(a) and 4(b) are not drawn. Furthermore, in the case of $4s\,{}^3P^0$–$4P\,{}^3D$ and

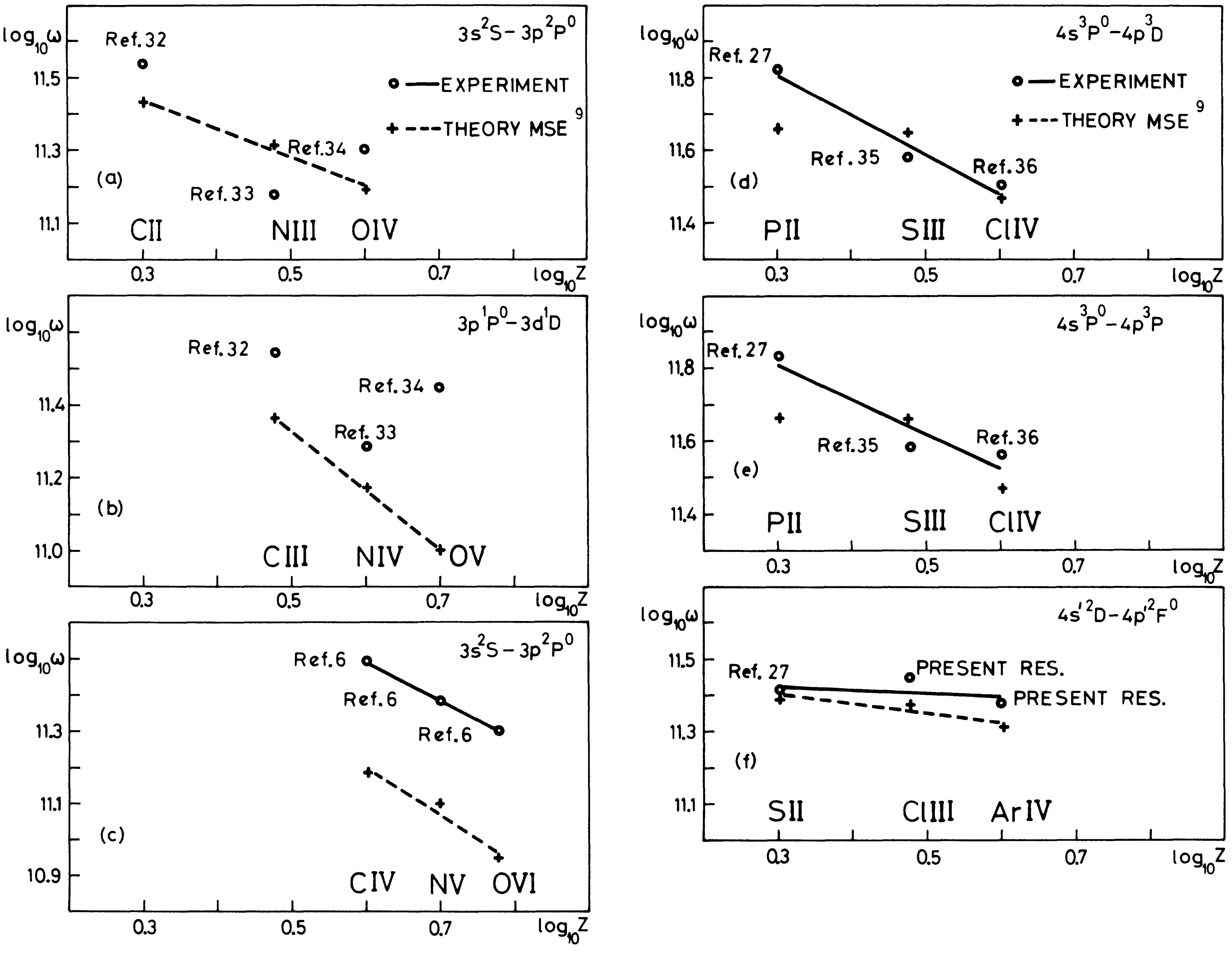


FIG. 4. Stark width ω (in frequency units) dependence upon effective nuclear charge Z. Results are normalized to (a) $N_e=1\times10^{17}$ cm^{-3} and $T_e=35\,000$ K, (b) 38 000 K, (c) 145 000 K, (d) and (e) 11 600 K, and (f) 31 000 K.

TABLE V. Width and shift dependence upon effective nuclear charge for several sequences of ions derived from data in Figs. 2 and 4.

Sequence of ions	Transition	Ions studied	T_e (K)	Z dependence derived from			
				widths		shifts	
				exp.	theor.	expt.	theor.
Li-like	$3s\ ^2S - 3p\ ^2P^0$	C IV-O VI	145 000	$Z^{-1.05}$	$Z^{-1.32}$		
Be-like	$3p\ ^1P^0 - 3d\ ^1D$	C III-O V	38 000		$Z^{-1.62}$		
B-like	$3s\ ^2S - 3p\ ^2P^0$	C II-O IV	35 000		$Z^{-0.79}$		
Si-like	$4s\ ^3P^0 - 4p\ ^3D$	P II-Cl IV	11 600	$Z^{-1.08}$			
	$4s\ ^3P^0 - 4p\ ^3P$	P II-Cl IV	11 600	$Z^{-0.94}$			
P-like	$4s\ ^4P - 4p\ ^4D^0$	S II-Ar IV	31 000	$Z^{-0.28}$	$Z^{-0.30}$	$Z^{-0.95}$	$Z^{-0\ 52}$
	$4s'\ ^2D - 4p'\ ^2F^0$	S II-Ar IV	31 000	$Z^{-0.08}$	$Z^{-0.27}$		

$4s\ ^3P - 4p\ ^3P$ transitions of Si-like ions, Figs. 4(d) and 4(e), the best fit line through theoretical data points has not been set, either. Namely, due to the existence of a very close perturbing level $3d$ in the case of P II, theoretical results do not show linear dependence upon z [see our log-log graphs in Figs. 4(e) and 4(d)].

Finally, we draw attention to some regularities and similarities of experimental Stark widths and shifts in Tables II and III. If one compares experimental widths (converted into frequency units) in these tables, good agreement will be found with the general study of regularities and similarities in plasma broadened spectral line-widths by Wiese and Konjević.[5] Linewidths within the multiplet agree within a few percent. Line widths within two multiplets $4s'\ ^3D^0 - 4p'\ ^3P$ and $4s'\ ^3D^0 - 4p'\ 3D$ which belong to the same supermultiplet of Ar III, Table I, are the same within 20%. Furthermore, the inspection of Stark shifts (converted into frequency units) shows the same type of regularities: shifts within a multiplet are the same within a few percent and shifts within two multiplets belonging to the supermultiplet of Ar III are the same within 30%. Similar findings for shifts have been detected recently in the study of the line shifts of halogen atoms.[8,37,38]

V. CONCLUSIONS

We report here the results of Stark widths and shift measurements of two Cl II, two S II, six Ar III, five Cl III, and four Ar IV lines. Most of these results, in particular for shifts, are reported for the first time. These results are compared with theoretical data. For this purpose we performed calculations of the corresponding widths and shifts using modified semiempirical formulas.[9,10] The results of comparison with experiment are given in Tables II and III. For the Stark widths and shifts the average ratios of the measured to calculated values are

	w_m / w_{MSE}	d_m / d_{MSE}
Cl II	1.34	1.59
C II	1.06	1.54
Cl III	1.11	1.72
Ar III	1.11	1.02
Ar IV	1.09	1.03

These results clearly illustrate the usefulness of MSE (Refs. 9 and 10) for estimation of Stark widths and shifts. However, it should be noticed that theoretical widths and shifts are systematically lower than the experimental ones although well within the limits of the estimated uncertainty of both experiment and theory. Here we should underline the importance of completeness of the set of perturbing levels used in evaluating Stark widths and shifts particularly, see Figs. 1 and 2. An incomplete set of perturbing levels taken in evaluation of Stark shifts of Ar IV lines affects considerably the results, and in this particular case by pure change gives good agreement between theory and experiment. For all ions with an incomplete set of perturbing levels, simple low-temperature limit MSE formulas[11] are recommended whenever the $3kT/2\Delta E \leq 2$ condition is fulfilled (see examples in Fig. 2).

Study of regularities of the Stark widths within multiplet and supermultiplet of investigated ions proves once more the results of general study of regularities and similarities of Stark widths.[5] Furthermore, the inspection of Stark shifts shows the same type of regularities: shifts within multiplet are the same within few percent, and shifts within supermultiplet within 30%. It has been already noticed[5,6] that Stark widths of analogous transitions gradually decrease along isoelectronic sequence of ions. Here we present some new results which show the same tendency. Clear correlation between the disposition of perturbing energy levels and the decrease of Stark width along the sequence of isoelectronic ions exists (see Fig. 1). From our results and from other experimental data the dependence of Stark widths upon effective ion charge (see Fig. 4) of isoelectronic ions is determined. The results are given in Table V. A similar tendency along the sequence of isoelectronic ions for the shifts is detected for the first time (see Fig. 2). Our results in Fig. 3, indicate that shifts decrease faster along the sequence.

ACKNOWLEDGMENTS

This work is based on the work supported by the U.S. Yugoslav Joint Fund for Scientific and Technological Cooperation in cooperation with the National Institute of Standards and Technology under Grant No. 586. We would also like to thank V. Kršljanin for the calculation of MSE shifts.

*Permanent address: Institute of Physics, Faculty of Natural Sciences, 21000 Novi Sad, Yugoslavia.

[1] N. Konjević and J. R. Roberts, J. Phys. Chem. Ref. Data **5**, 209 (1976).

[2] N. Konjević and W. L. Wiese, J. Phys. Chem. Ref. Data **5**, 259 (1976).

[3] N. Konjević, M. S. Dimitrijević, and W. L. Wiese, J. Phys. Chem. Ref. Data **13**, 619 (1984).

[4] N. Konjević, M. S. Dimitrijević, and W. L. Wiese, J. Phys. Chem. Ref. Data **13**, 649 (1984).

[5] W. L. Wiese and N. Konjević, J. Quant. Spectrosc. Radiat. Transfer **28**, 185 (1982).

[6] F. Böttcher, P. Breger, J. D. Hey, and H.-J. Kunze, Phys. Rev. A **38**, 2690 (1988).

[7] J. Purić, M. Cuk, and I. S. Lakićević, Phys. Rev. A **32**, 1106 (1985).

[8] S. Djurović and N. Konjević, Z. Phys. D **11**, 113 (1989).

[9] M. S. Dimitrijević and N. Konjević, J. Quant. Spectrosc. Radiat. Transfer **24**, 451 (1980).

[10] M. S. Dimitrijević and V. Kršljanin, Astron. Astrophys. **165**, 269 (1986).

[11] M. S. Dimitrijević and N. Konjević, Astron. Astrophys. **172**, 345 (1987).

[12] R. Kobilarov, M. V. Popović, and N. Konjević, Phys. Rev. A **37**, 1021 (1988).

[13] R. Kobilarov, N. Konjević, and M. V. Popović, Phys. Rev. A **40**, 3871 (1989).

[14] J. T. Davies and J. M. Vaughan, Astrophys. J. **137**, 1302 (1963).

[15] J. Purić and N. Konjević, Z. Phys. **249**, 440 (1972).

[16] D. E. T. F. Ashby and D. F. Jephcott. Appl. Phys. Lett. **3**, 13 (1963).

[17] T. L. Pittman and C. Fleurier, in *Spectral Line Shapes*, edited by K. Burnett (de Gruyter, Berlin, 1983), Vol. 2.

[18] C. Fleurier and P. le Gall, J. Phys. B **17**, 4311 (1984).

[19] T. L. Pittman and C. Fleurier, Phys. Rev. A **33**, 1291 (1986).

[20] A. Gawron, S. Maurman, F. Böttcher, A. Meckler, and H.-J. Kunze, Phys. Rev. A **38**, 4737 (1988).

[21] W. L. Wiese, M. W. Smith, and B. M. Glenon, *Atomic Transition Probabilities, Hydrogen through Neon,* Natl. Bur. Stand. Ref. Data Ser., Natl. Bur. Stand. (U.S.), No. NSRDS-NBS 4 (U.S. GPO, Washington D.C., 1966), Vol. I.

[22] C. E. Moore, *Atomic Energy Levels as Derived from the Analysis of Optical Spectra,* Natl. Bur. Stand. (U.S.) Circ. No. 35 (U.S. GPO, Washington, D.C., 1971).

[23] C. E. Moore, *Ionization Potentials and Ionization Limits Derived from the Analysis of Optical Spectra,* Natl. Bur. Stand. (U.S.) Circ. No. 34 (U.S. GPO, Washington, D.C. 1970).

[24] J. D. Hey, A. Gawron, X. J. Xu, P. Breger, and H.-J. Kunze, J. Phys. B **22**, 241 (1989).

[25] H. R. Griem, *Spectral Line Broadening by Plasmas* (Academic, New York, 1974).

[26] J. M. Bridges and W. L. Wiese, Phys. Rev. **159**, 31 (1967).

[27] M. H. Miller, D. Abadie and A. Lesage, Astrophys. J. **291**, 219 (1985).

[28] S. Mar, A. Chernichowski, and J. Chapelle, in *Spectral Line Shapes,* edited by F. Rostas (de Gruyter, Berlin, 1985).

[29] M. Platiša, M. Dimitrijević, M. Popović, and N. Konjević, Astron. Astrophys. **54**, 837 (1977).

[30] M. Platiša, M. Popović, M. S. Dimitrijević, and N. Konjević, Z. Naturforsch. Teil A **30**, 212 (1975).

[31] J. Purić, S. Djeniže, A. Srećković, M. Cuk, J. Labat, and M. Platiša, Z. Phys. D **8**, 343 (1988).

[32] S. Djeniže A. Srećković, M. Milosavljević, O. Labat, and J. Purić, Z. Phys. D **9**, 129 (1988).

[33] J. Purić, A. Srećković, S. Djeniže, and M. Platiša, Phys. Rev. A **36**, 3957 (1987).

[34] J. Purić, S. Djeniže, A. Srećković, M. Platiša, and J. Labat, Phys. Rev. A **37**, 498 (1988).

[35] M. Platiša, M. Popović, M. Dimitrijević, and N. Konjević, J. Quant. Spectrosc. Radiat. Transfer **22**, 333 (1979).

[36] J. Purić, A. Srećković, S. Djeniže, and M. Platiša, Phys. Rev. A **37**, 4380 (1988).

[37] S. Djurović, R. Konjević, M. Platiša, and N. Konjević, J. Phys. B **21**, 739 (1988).

[38] S. Djurović and N. Konjević, Z. Phys. D **10**, 425 (1988).