Influence of ion dynamics on the width and shift of isolated He I lines in plasmas. II

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Stark widths and shifts of the He I 7065-, 6678-, 5016-, 4713-, and 3188-Å lines are measured in hydrogen-helium plasma. A repetitively pulsed low-pressure arc is used as a plasma source, while the signal averaging technique is employed to record the line profiles. The electron densities in the range of $(2.5-5.9)\times 10^{15}$ cm^{-3} are measured by 10.6-μm laser interferometry. The electron temperatures ranging from 19 300 to 23 600 K are determined from the ratio of the H_γ line intensity to the underlying continuum, while the gas temperatures from 5000 to 12 600 K are measured from the Doppler component of the He I line profiles. The experimental Stark widths and shifts are compared with the theoretical results obtained from the three sets of semiclassical calculations of Stark broadening parameters by using the quasistatic and ion-dynamic treatment of the ions. Inclusion of ion dynamics in the width and shift calculations improves the consistency in the comparison between the theory and the experiment and shows the systematic discrepancy between three semiclassical calculations. These results suggest the possibility of high precision electron-density diagnostics.

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I. INTRODUCTION

In this paper we present results of the experimental study of the Stark broadening and shifting of five isolated spectral lines of neutral helium in a plasma of a low-pressure pulsed arc. Helium energy levels for investigated lines and for our plasma conditions are "isolated" in the sense that l levels are not degenerate and do not overlap one another. This single l level experiences a relatively small second order (quadratic) Stark shift that, when smeared out by the plasma electric field distribution, causes the Lorentzian electron broadened line to become asymmetrical. While static ion effects are much smaller for isolated helium lines (quadratic Stark effect) than for hydrogen lines (linear Stark effect), they are larger for helium lines than any species except hydrogenic ones. Apart from static ion effects on the line shape there is the possibility of ion dynamical effects near the line center where ions may behave more like electrons, resulting in impact type broadening. The inclusion of ion dynamics in theoretical calculations also produces asymmetrical line profiles but with larger widths and shifts than in the case when only the quasistatic ion approximation is applied.

The method for evaluation of the influence of ion-dynamic effects on the shape of nonhydrogenic atom lines is developed independently by Griem [1] and Barnard, Cooper, and Smith (BCS) [2]. In both cases the influence of ions is included through both the quasistatic and ion-dynamic approximations. In the calculations of the line shapes enter electron impact half–half-width w_e, electron impact shift d_e, and ion-broadening parameter A. These three quantities are calculated by several authors [1,3–5] for a number of atoms and their spectral lines. A summary of both theoretical approaches, which involve ion dynamics in the evaluation of the atomic line shapes [1,2], is given in an experimental paper on neutral helium lines [6], while an experimental verification of the importance of ion dynamics for the evaluation of widths and shifts for two helium 3889- and 5876-Å lines has recently been reported by Kobilarov, Konjević, and Popović [7] (see also [8]). In that paper [7] it has been shown that the inclusion of ion-dynamic effects in a comparison between experiment and theory of the Stark broadening explains some systematic discrepancies detected at lower electron densities, which is also of importance for precision plasma diagnostics. Furthermore, the results of the comparison between the experiment and theoretical data show a constant systematic discrepancy between the three sets of semiclassical calculations of Stark broadening parameters w_e, d_e, and A for two investigated He I lines [1,3–5] that may be of importance for further development of the theories. This paper is an extension of our first study of the ion-dynamic influence on the width and shift of two He I lines [7]. Here, we report the results of the study of an additional five prominent He I lines. In order to achieve a better quality of line shape and shift recordings at lower electron densities when ion-dynamic effects are of greater importance, the new repetitively pulsed plasma source is built and the signal averaging technique for the light detection is applied. For the electron-density diagnostics a 10.6-μm CO_2 laser interferometer is used, while for determination of electron temperature T_e and gas temperature T_g the standard spectroscopic diagnostic techniques are used. The experimental results of investigated He I lines are compared with the theoretical results obtained by using the static and ion-dynamic approximation. Several theoretical calculations of Stark broadening parameters w_e, d_e, and A for the He I lines are tested.

II. THEORY

Both theoretical approaches [1,2] for evaluation of the influence of ion dynamics to the width and shift of the plasma broadened isolated nonhydrogenic neutral atom lines are very similar. The correspondence between the quantities used by Griem [1] and Barnard, Cooper, and Smith [2] is given in [6]. Here, we used the results and notation of BCS theory [2]. In order to make a comparison, widths and shifts are calculated using the quasistatic ion approximation [1] as well. To facilitate further comparison only the final formulas used for evaluation of the linewidths and shifts are given here.

For a nonhydrogenic isolated neutral atom line the ion broadening is not negligible and the line profiles are described by an asymmetric function $j_{A,R}(x)$ [1]. In this case the full half-width w and shift at the half-width d may be calculated from the following equations [1,2,6,7]:

$$w = w_e(1+gW_j A_N)N_e 10^{-16} , \tag{1}$$

$$d = (d_e \pm 3.2 g_1 A_N D_j w_e)N_e 10^{-16} , \tag{2}$$

where $g = 1.75(1-0.75R)$, $R = 0.090 N_e^{1/6} T_e^{-1/2}$, $A_N = A N_e^{1/4} 10^{-4}$, $g_1 = g/1.75$, and

$$W_j = \begin{cases} 1.36B^{-1/3}/g, & B < (1.36/g)^3 \\ 1, & B \geq (1.36/g)^3, \end{cases} \tag{3}$$

$$D_j = \begin{cases} (2.35B^{-1/3} - 3A_N^{1/3}R)/2g_1, & B < 1 \\ 1, & B \geq 1, \end{cases} \tag{4}$$

where $B = A_N^{1/3}(0.0806 w_e/\lambda^2 N_e^{2/3})(\mu/T_g)$ with atom-ion perturber reduces mass μ in amu and gas temperature T_g. In the case when $W_j = 1$ and/or $D_j = 1$ the influence of ion dynamics is negligible and the line shape is treated using the quasistatic ion approximation [1]. In this situation it is necessary to estimate the Debye shielding correction for the width and/or shift (see Appendix IV in [1]). BCS theory [2] includes the Debye shielding correction.

For the evaluation of theoretical (quasistatic and ion-dynamic) Stark widths and shifts of the He I lines w_e, d_e, and A are taken from Benett and Griem [1,3] and Bassalo, Cattani, and Walder [4]. The third comparison was made by using the results of Dimitrijević and Sahal-Brechot [5], in spite of the fact that they used the impact theory to estimate the contribution of ion broadening to the linewidth. This method produces the symmetric line profiles while the asymmetric line shapes are actually observed. In this paper [5] electron impact and proton impact widths w_e, w_p and shifts d_e, d_p are reported for different He I lines at various electron densities N_e and electron temperatures T_e. The total half-width (or shift) at certain N_e and T_e is then simply the sum of two half-widths (or shifts). Here we assumed that protons are only perturbers in our plasma. This is a reasonable assumption for our helium-hydrogen plasma; see Sec. IV.

A comparison with the experiment was done by using the electron impact half–half-widths and shifts from [5], while the ion broadening parameter A was taken from Benett and Griem [1,3]. Total half-widths and shifts were calculated from Eqs. (1) and (2).

III. EXPERIMENT

A. Plasma source and experimental procedure

A low-pressure pulsed arc is used as a plasma source; see Fig. 1. It consists of a low-inductance, 2.5-μF discharge capacitor and discharge tube. The pulsed arc is fired at 4 kV by a grounded-grid thyratron with a repetition rate of 2 Hz. The discharge circuit is realized with the damping resistor so the discharge current was critically damped. The discharge current with the peak value 700 A lasted about 10 μs and showed the high shot-to-shot reproducibility (within $\pm 2\%$). The discharge vessel is made of a 10-mm internal diameter alumina tube. The distance between electrodes is 165 mm. The holes, 3 mm in diameter, are located at the center of both aluminum electrodes to facilitate the optical alignment and to perform spectroscopic and laser interferometric measurements.

As a source of unshifted He I line profiles a Geissler tube is used. The only exception is a 3188-Å line when a low-pressure tube with microwave excitation is em-

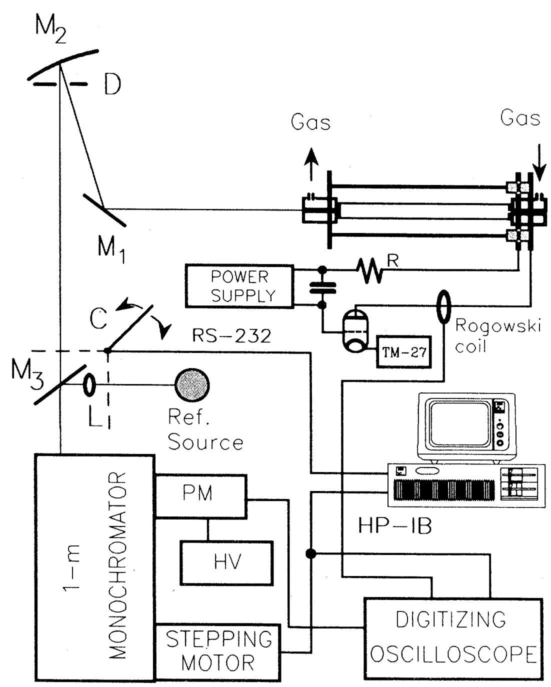

FIG. 1. Schematic diagram of the experimental setup.

ployed. By using the chopper C controlled by a personal computer (PC) through interface type RS232 (see Fig. 1), the light from the pulsed arc and from the reference source is observed alternately without changing the monochromator wavelength setting.

The light emitted from the arc is focused by a concave mirror M_2 onto the entrance slit of a 1-m monochromator equipped with a 1200-g/mm grating and a stepping motor with 36 000 steps/rev, controlled by a PC through the Hewlett-Packard Interface Bus (HP-IB). With the exception of 3188 Å, the helium lines are recorded with 15-μm slits (measured instrumental half-width 0.16 Å). For the 3188-Å line 20-μm slits (0.21-Å instrumental half-width) are used. The diaphragm D (10 mm diameter) placed in front of the concave mirror M_2 (see Fig. 1) ensures that the observed light is coming only from the narrow cone around the arc axis. The light from the reference source is focused by a lens L onto the entrance slit of the monochromator. Using the partially reflecting mirror M_3 the light from the arc and reference source has the same optical path from M_3 to the monochromator. The photomultiplier is used for the light intensity recordings.

Our main concern for the He I line-shape measurements was the possible distortion arising from self-absorption, which depends on the observed plasma length and on the emitter's density. With the fixed plasma length the effect of self-absorption is possible to control by emitter density, which depends on the composition of a used gas mixture. In this experiment a mixture of helium and hydrogen is used. The ratio of hydrogen and helium in the mixture is determined in the following way: The amount of helium is gradually decreased while the half-widths of strongest investigated lines (6678 and 5016 Å) are measured under the same experimental conditions, until the linewidths become constant, i.e., optically thin conditions are reached. For the final investigations of He I line shapes, a H_2-He, 80:20 % gas mixture is selected. In this gas mixture the optically thin conditions for the strongest lines are reached while a sufficient intensity for weak line recordings still remains. During the experiment, the continuous flow of the gas mixture is sustained at a pressure of 1.7 mbar.

The signals from the photomultiplier are transmitted to the digitizing oscilloscope working in an averaging mode. Each experimental point represents an average of 64 samples. The oscilloscope is triggered by a signal from the Rogowski coil; see Fig. 1. The spectra are recorded 21, 23, 25, and 27 μs after the peak of the discharge current. The control of the oscilloscope and data acquisition is also performed by a PC through the HP-IB interface. The spectral intensities of the light emitted from the reference source are taken as an average of 64 samples, each of them lasting 100 μs. The examples of He I 4713- and 7065-Å experimental line profiles recorded from the pulsed arc plasma and from the reference source are given in Figs. 2(a) and 2(b). In Fig. 2(b) one can clearly distinguish, on the lower trace (from the reference source), the two lines that are fine structure components of the $2\,^3P^o-3\,^3S$ transition.

In order to determine the center of the unshifted line

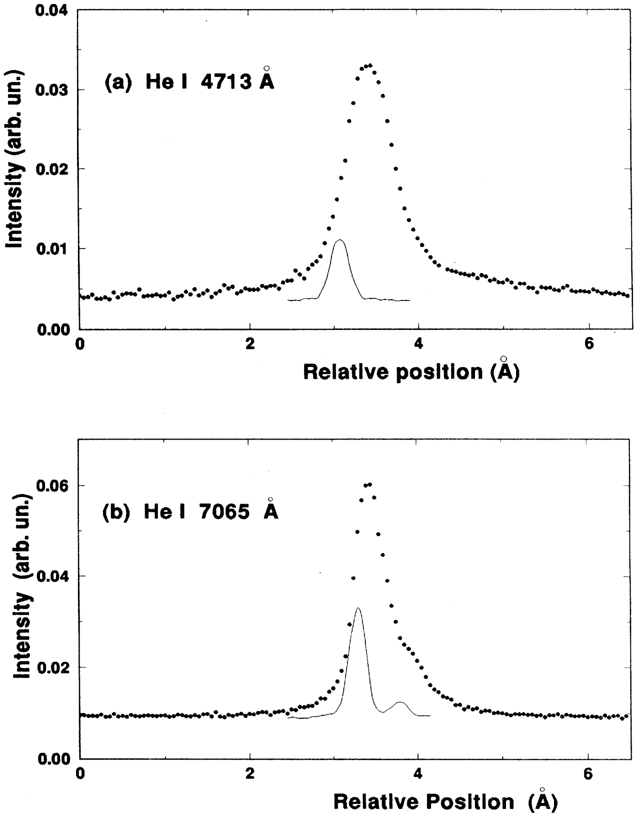

FIG. 2. Simultaneously recorded He I 4713- and 7065-Å line profiles from the pulsed arc plasma (broadened profile) and from the reference source.

the recorded spectral line profile from the reference source is fitted with the Gaussian. In this way, the instrumental half-width is measured at the same time. Under our experimental conditions for all He I lines recorded from the pulsed arc plasma the contribution of instrumental and Doppler broadening to the measured linewidths was not negligible. Therefore, to obtain a Stark profile it was necessary to use a deconvolution procedure for Gaussian (instrumental and Doppler) and asymmetric $j_{A,R}(x)$ (Stark for neutral atom lines) profiles [9]. Knowing the instrumental half-width from the Gaussian part of the experimental profile it is possible to determine the Doppler width as well as gas temperatures.

TABLE I. Experimental electron density N_e, electron temperature T_e, and gas temperature T_g at various times of the plasma decay when Stark widths and shifts are measured. Estimated errors are given also.

τ (μs)	N_e (10^{15} cm^{-3})	T_e (K)	T_g (K)
21	5.9($\pm$0.4)	23 600($\pm$3500)	12 600($\pm$1500)
23	4.5($\pm$0.3)	22 700($\pm$3400)	9200($\pm$900)
25	3.4($\pm$0.3)	21 400($\pm$3600)	7200($\pm$1200)
27	2.5($\pm$0.2)	19 300($\pm$4000)	5000($\pm$1000)

TABLE II. Experimental widths w_m with estimated errors, and ratios of measured and calculated widths using the static w_{st} and dynamic-ion w_{dyn} approximations. Data for the theoretical calculations are taken from Benett and Griem (BG) [1,3], Bassalo, Cattani, and Walder (BCW) [4], and Dimitrijević and Sahal-Brechot (DSB) [5]. For the ratios marked DSB+BG theoretical results are calculated using the electron impact half–half-width w_e from [5] and the ion-broadening parameter A from [1,3].

τ	λ	w_m	w_m/w_{st}				w_m/w_{dyn}			
(μs)	(Å)	(Å)	BG	BCW	DSB	DSB+BG	BG	BCW	DSB	DSB+BG
21	5016	0.47±0.040	1.02	1.07		1.18	0.90	0.94	1.06	1.08
23		0.38±0.035	1.09	1.15		1.26	0.96	1.01	1.09	1.17
25		0.27±0.025	1.03	1.09		1.20	0.92	0.96	1.03	1.11
21	6678	0.57±0.040	1.17	1.32		1.31	0.97	1.09	1.10	1.16
23		0.43±0.035	1.17	1.31		1.31	0.99	1.10	1.08	1.17
25		0.32±0.035	1.17	1.30		1.30	1.00	1.09	1.06	1.16
27		0.22±0.025	1.11	1.20		1.23	0.94	1.02	1.01	1.11
21	7065	0.29±0.030	0.95	1.08		1.26	0.85	0.95	1.09	1.09
23		0.22±0.025	0.96	1.08		1.25	0.85	0.95	1.09	1.08
25		0.17±0.020	0.98	1.18		1.30	0.88	0.98	1.13	1.10
21	4713	0.54±0.040	0.91	1.04		1.27	0.85	0.96	1.17	1.21
23		0.41±0.035	0.92	1.04		1.27	0.86	0.96	1.17	1.21
25		0.31±0.025	0.92	1.05		1.28	0.85	0.97	1.19	1.21
27		0.23±0.020	0.94	1.08		1.29	0.87	0.99	1.20	1.23
21	3188	0.43±0.040	0.93	1.05		1.19	0.89	1.00	1.12	1.17
23		0.32±0.030	0.91	1.03		1.17	0.87	0.97	1.09	1.15
25		0.26±0.025	0.98	1.12		1.26	0.93	1.05	1.16	1.23

The influence of fine structure splitting on the measurements of the width and shift of He I triplet lines is estimated by the procedure described in [6]. The estimated contributions of van der Waals [10] and resonance broadening [11] to the experimental line profiles are found to be negligible for our plasma conditions.

B. Plasma diagnostics

A CO_2 laser interferometer at 10.6 μm with a plane external mirror was used to determine the electron density. To perform these measurements the quartz windows at both ends of the discharge tube are replaced with

TABLE III. Same as for Table II, but for the shifts.

τ	λ	d_m	d_m/d_{st}				d_m/d_{dyn}			
(μs)	(Å)	(Å)	BG	BCW	DSB	DSB+BG	BG	BCW	DSB	DSB+BG
21	5016	0.15±0.010	1.08	0.99		0.85	0.64	0.60	0.79	0.51
23		0.12±0.010	1.09	0.99		0.88	0.64	0.60	0.73	0.53
25		0.09±0.010	1.10	1.00		0.90	0.65	0.61	0.69	0.53
21	6678	0.23±0.015	1.23	1.60		0.97	0.67	0.79	0.97	0.54
23		0.16±0.010	1.24	1.51		0.93	0.68	0.76	0.89	0.52
25		0.13±0.010	1.29	1.66		1.03	0.74	0.84	0.95	0.58
27		0.09±0.010	1.23	1.58		1.01	0.71	0.82	0.91	0.57
21	7065	0.19±0.010	1.24	1.35		0.81	0.90	0.96	1.03	0.62
23		0.14±0.010	1.21	1.30		0.78	0.88	0.92	0.98	0.59
25		0.11±0.010	1.27	1.34		0.81	0.92	0.95	0.99	0.62
21	4713	0.34±0.015	1.22	1.28		1.02	0.97	0.99	1.04	0.81
23		0.27±0.015	1.25	1.33		1.05	0.98	1.03	1.08	0.84
25		0.20±0.010	1.23	1.30		1.03	0.96	1.00	1.04	0.82
27		0.15±0.010	1.23	1.32		1.04	0.97	1.02	1.08	0.83
21	3188	0.17±0.010	1.31	1.40		1.08	0.97	1.00	1.29	0.83
23		0.13±0.010	1.34	1.41		1.09	0.99	1.00	1.31	0.84
25		0.10±0.010	1.38	1.42		1.12	1.01	1.01	1.35	0.85

ZnSe. Radiation at 10.6 μm is detected with a liquid nitrogen cooled infrared PbSnTe detector.

The electron temperature is determined from a line-to-continuum ratio of H_γ spectral lines [11]. The gas temperature is determined as an average, from the Doppler half-widths of all recorded He I spectral line profiles.

IV. EXPERIMENTAL RESULTS AND DISCUSSION

Experimentally determined plasma electron densities N_e and corresponding electron T_e and gas T_g temperatures at various times of plasma decay τ are given together with estimated errors in Table I. The estimated errors ranging from 6% to 8% for the electron densities are derived from the uncertainties in plasma length measurements and in the determination of an interference fringe number. The largest factor in estimating the results of T_e measurements is the uncertainty in the measurement intensity of the weak continuum below the hydrogen H_γ line.

The experimental results at various times τ of plasma decay for the Stark widths w_m and Stark shifts d_m of the investigated He I lines together with estimated errors are given in Tables II and III, respectively. The results w_m and d_m in Tables II and III are compared with the static theoretical data w_{st} and d_{st} calculated from Eqs. (1) and (2) with $W_j = D_j = 1$. The theoretical results obtained using the data for electron impact half–half-width w_e, shift d_e, and ion broadening parameter A of Benett and Griem [1,3] and Bassalo, Cattani, and Walder [4] are given in Tables II and III in the columns denoted as BG and BCW, respectively. The theoretical data calculated with w_e from Dimitrijević and Sahal-Brechot [5] and with ion broadening parameter A from [1,3] are given in column DSB+BG. The experimental results w_m and d_m are also compared with the ion-dynamic theory, and in this case w_{dyn} and d_{dyn} are calculated from Eqs. (1) and (2). The required data are taken from BG [1,3], the BCW [5], DSB+BG [5] and [1,3], and DSB [5]. It is important to notice here that in the evaluation of the ion-dynamic widths and shifts an important assumption is made concerning the type of ions present in our plasma. Namely, due to the large difference in ionization potentials and due to the large concentration of hydrogen (H_2:He=80:20 %) in our initial gas mixture, we assumed that only H^+ ions are present in the plasma.

Since we also used the data from other experiments for the comparison, the corresponding theoretical widths and shifts were calculated by using both the quasistatic and ion-dynamic approximations in the way described for our data. The ratios of measured widths and shifts to the theoretical ones are compared as described in our first paper; see Figs. 4–6 in [7]. The average values of the ratio w_m/w_{dyn} and d_m/d_{dyn} for all available experimental data with the estimated uncertainties smaller then ±30% in critical reviews [12] are given in Table IV. Due to the large scatter of the experimental data, the recent comprehensive results for He I lines [13] are not taken for this comparison.

The inclusion of ion dynamics in the comparison improves the consistency between various sets of experimental data obtained at different plasma conditions and in this indirect way justifies the application of the ion-dynamic correction [1,2] to the widths and shifts, in particular at lower electron densities. Due to the smaller effect of ion dynamics on the widths (uncertainties of the experimental widths exceed the difference between the quasistatic and ion-dynamic approximations) this conclusion may be applied with more certainty to the shifts.

The average ratios of the experimental widths and shifts to the corresponding theoretical results with ion dynamics are given together (in parentheses) with the maximal scatter from the average value; see Table V. Here it should be noted that the data in Table V represent the average ratios of Ref. [6] and our experimental data. We only selected Ref. [6] for two reasons: (i) This reference reports the results for all investigated lines and (ii) an estimated accuracy of these data exceeds most of the other reliable data. Results for the 3889- and 5876-Å lines are taken from [7]. The ratios in Table V can be used for two purposes: first, for further refinement of the theory, and second, knowing the ratios in this table

TABLE IV. Ratios w_m/w_{dyn} and d_m/d_{dyn} for the experimental results for the five investigated He I lines. All data of the other authors are with estimated uncertainties smaller than ±30% in the critical reviews [12]. Data for the theoretical calculations are taken from Benett and Griem [1,3].

λ (Å)	w_m/w_{dyn}	d_m/d_{dyn}	Ref.
5016	0.67		[15]
	0.85	0.75	[16]
	0.86	0.50	[17]
		0.91	[18]
		0.59	
	0.92		[20]
	0.92		
	1.04		[21]
	0.91		
	0.89		[22]
	0.95		
	0.93	0.70	[6]
	0.93	0.64	a
6678	0.98	0.68	[6]
	0.98	0.70	a
7065	0.86		[19]
	0.82	0.88	[6]
	0.86	0.90	a
4713	0.85		[15]
	1.02	0.93	[16]
	0.91	0.96	[17]
	0.93	1.48	[18]
	0.56	0.97	
	0.89	0.93	[6]
	0.86	0.97	a
3188	1.00	0.89	[16]
	0.93		[22]
	1.15		
	0.92	0.94	[6]
	0.90	0.99	a

[a]Our results.

TABLE V. Average ratios of the measured He I linewidths w_m, and shifts d_m to the theoretical results w_{dyn} and d_{dyn}, respectively. The ratios for 3889- and 5876-Å lines are taken from [7]. BG, BCW, and DSB denote ratios with theoretical results using data from Benett and Griem [1,3], Bassalo, Cattani, and Walder [4], and Dimitrijević and Sahal-Brechot [5], respectively. Theoretical results marked DSB+BG are calculated with electron impact half–half-widths w_e from [5] and ion-broadening parameter A from [1,3].

λ		$\overline{w_m/w_{dyn}}$				$\overline{d_m/d_{dyn}}$			
(Å)	Transition	BG	BCW	DSB	DSB+BG	BG	BCW	DSB	DSB+BG
5016	$2\,^1S-3\,^1P^o$	0.93(0.03)	0.97(0.04)	1.07(0.04)	1.11(0.06)	0.66(0.02)	0.62(0.02)	0.79(0.10)	0.58(0.07)
6678	$2\,^1P^o-3\,^1D$	0.98(0.04)	1.07(0.05)	1.07(0.06)	1.13(0.04)	0.70(0.04)	0.79(0.05)	0.91(0.06)	0.58(0.06)
7065	$2\,^3P^o-3\,^3S$	0.85(0.03)	0.95(0.03)	1.10(0.03)	1.13(0.05)	0.90(0.02)	0.94(0.02)	1.03(0.05)	0.67(0.08)
3889	$2\,^3S-3\,^3P^o$	0.85(0.03)	0.98(0.03)	0.99(0.06)	1.03(0.03)	0.79(0.04)	0.95(0.04)	0.93(0.18)	0.83(0.06)
5876	$2\,^3P^o-3\,^3D$	0.90(0.02)	1.17(0.02)	1.04(0.07)	1.05(0.02)	0.72(0.04)	0.46(0.03)	1.16(0.22)	a
4713	$2\,^3P^o-4\,^3S$	0.86(0.01)	0.98(0.02)	1.19(0.02)	1.21(0.01)	0.96(0.02)	1.00(0.03)	1.04(0.04)	0.84(0.03)
3188	$2\,^3S-4\,^3P^o$	0.90(0.03)	1.02(0.05)	1.14(0.05)	1.19(0.04)	0.98(0.03)	0.99(0.02)	1.26(0.09)	0.87(0.04)

[a]Theory predicts a sign opposite from the experimental shift.

one can use any of the three theoretical approaches [1,4,5] in conjunction with one's measurements of widths and/or shifts for high-precision plasma diagnostics. This applies in particular to the results of the 4713-Å line, which suggests that He I lines may be used for plasma diagnostic purposes with an accuracy exceeding that achieved with the H_β line [14]. Of course, this precision may be achieved at lower electron density only if the correction for the contribution of ion motion to the linewidth or shift [2] is considered.

V. CONCLUSIONS

In this paper we present the results of the precise measurements of Stark widths and shifts for five He I lines. The shapes and shifts of these lines are measured in hydrogen-helium plasma of a repetitively pulsed low-pressure arc in the electron-density range $(2.5-5.9)\times10^{15}$ cm^{-3}. The electron and gas temperatures were in the range 19 300–23 600 K and 5000–12 600 K, respectively.

The experimental results are compared with the data from semiclassical calculations by Benett and Griem [1,3], Bassalo, Cattani, and Walder [4], and Dimitrijević and Sahal-Brechot [5] by using the quasistatic [1] and ion-dynamic [2] approximations. The overall trend of the results appears to favor the application of ion-dynamic theories [1,2] at lower electron densities, although the distinction from the quasistatic ion approximation is not clear cut for widths. The data from Table V can be used as a guide for the further development of the theory and high-precision plasma diagnostics.

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