Stark broadening parameters of the Kr II and Kr III spectral lines

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Stark widths and shifts of 14 singly (Kr II) and 11 doubly charged (Kr III) krypton ion spectral lines have been measured in the linear, low pressure, pulsed arc at 17 000 K electron temperature and 1.65×10^{23} m^{-3} electron density. The measured width and shift values have been compared to the theoretical data calculated by us by using the modified semiempirical method.

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I. INTRODUCTION

For the first time with the help of the Goddard high resolution spectrograph on the Hubble space telescope, krypton has been detected in the spectra of the interstellar medium [1,2], which represents the material from which the young early type stars (as, e.g., Ap and Bp type stars where Stark broadening data are of interest) are formed [3]. Moreover, krypton is present in many light sources and lasers as the working gas. If the Stark broadening is the principal pressure broadening mechanism in plasmas (with 10^{22}–10^{27} m^{-3} electron density), it is possible to obtain from Stark width and shift values other basic plasma parameters as, e.g., electron temperature (T) and density (N), essential for the stellar atmospheres modeling. Consequently, the knowledge of the Stark broadening parameters (the width and the shift) of ionized krypton (Kr II and Kr III) spectral lines is of interest for plasma diagnostic purpose.

Stark widths of Kr II spectral lines have been investigated in a number of references, starting with the first measurements, presented in Refs. [4–6]. For example, seven experiments from Refs. [7–13] have been performed within the 10 000 K and 17 400 K electron temperature range. These values show mutual scatter up to the factor 3. The theoretical Stark widths for several lines are given in Ref. [14]. Authors have calculated Stark widths (only for $T=10\,000$ K and $N=1\times10^{23}$ m^{-3}) by using Griem's semiempirical formula [15] and by using the approach based on the Born approximation with and without the empirical modification for the collision strength suggested by Robb (see Ref. [14]). Moreover, in Ref. [16] Stark widths of 37 Kr II lines, which belong to the $5s$-$5p$ and $5s'$-$5p'$ transitions, have been calculated within the modified semiempirical approach [17]. In the case of the Kr III spectrum only two experiments [18,19] deal with the Stark widths investigations of seven spectral lines. Calculations of the Kr III Stark widths have been performed in Refs. [18,20–24].

In the case of the Stark shift the situation is much different. Namely, from the first Kr II lines Stark shift investigation [4], only one experiment [10] provided reliable Stark line shifts of three Kr II spectral lines. We note here as well that today there are neither reliable Stark shift measurements nor theoretical Stark shifts for the Kr III specral lines. In Ref. [25], Kr II and Kr III line shifts have been investigated but without the reliable plasma parameter determination so that the comparison with our results is not possible.

In this paper we will present measured and calculated Stark FWHM (full width at half intensity maximum, W) and Stark shift (d) values of 14 Kr II and 11 Kr III spectral lines. Stark FWHM values of 2 Kr II and 7 Kr III lines and Stark shift values of 11 Kr II lines were not known before. To our knowledge, present d values of Kr III lines are the first published with reliably determined plasma parameters on this topic. In addition, to our knowledge, our calculated Stark widths of the $5p$-$5d$ Kr II lines are, also, the first theoretical data.

Measurements were been performed at 17 000 K electron temperature and 1.65×10^{23} m^{-3} electron density in krypton plasma created in the linear, low pressure, pulsed arc discharge. The W and d values were been calculated within the frame of the modified semiempirical method [17,20,26–31] for the electron temperature range between 10 000 and 70 000 K.

II. EXPERIMENT

The modified version of the linear low pressure pulsed arc [32–34] has been used as a plasma source. A pulsed discharge was driven in a quartz discharge tube of 5 mm inner diameter and effective plasma length of 7.2 cm (Fig. 1 in Refs. [32,33]). The tube has an end-on quartz window. On the opposite side of the electrodes the glass tube was expanded in order to reduce erosion of the glass wall and also sputtering of the electrode material onto the quartz windows. The working gas was pure krypton at 130 Pa filling pressure in flowing regime. Spectroscopic observation of isolated spectral lines was made end-on along the axis of the discharge tube. A capacitor of 14 μF was charged up to 1.5 kV. The line profiles were recorded using a shot-by-shot technique with a photomultiplier (EMI 9789 QB and EMI 9659B) and a grating spectrograph (Zeiss PGS-2, reciprocal linear dispersion 0.73 nm/mm in first order) system. The instrumental FWHM of 0.008 nm was determined by using the narrow spectral lines emitted by the hollow cathode discharge. The recorded profiles of these lines are Gaussian in shape within 8% accuracy within the range of the investi-

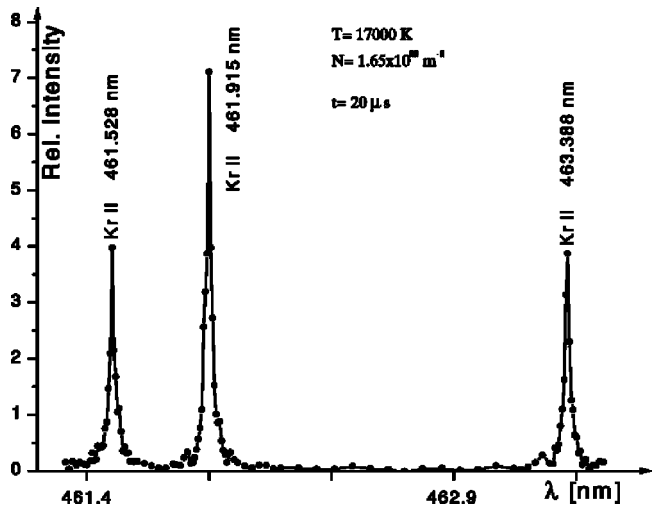

FIG. 1. Recorded Kr II spectrum at 20 μs after the beginning of the discharge.

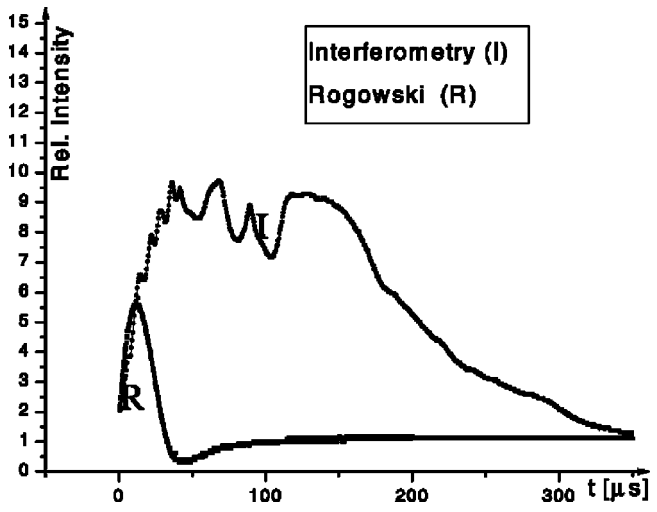

FIG. 3. Temporal evolution of the coil Rogowski (R) and interferometry (I) signals.

gated spectral line wavelengths. The spectrograph exit slit (10 μm) with the calibrated photomultiplier was micrometrically traversed along the spectral plane in small wavelength steps (0.0073 nm). The averaged photomultiplier signal (five shots at the same spectral range) was digitalized using an oscilloscope, interfaced to a computer. A sample output, as example, is shown in Figs. 1 and 2.

Plasma reproducibility was monitored by the Kr II line radiation and by the discharge current (it was found to be within 4%). Discharge characteristics were determined by analyzing the Rogowski coil signal. The found values were discharge current, 1.60 kA; discharge period, 82 μs; thermal resistance, 0.80 Ω; and decrement, 5.6. A typical Rogowski coil signal is presented in Fig. 3.

The measured profiles were of the Voigt type due to the convolution of the Lorentzian, Stark, and the Gaussian profiles from Doppler and instrumental broadening. For the electron density and temperature of our experiments the Lorentzian fraction in the Voigt profile was dominant (over 80%). van der Waals and resonance broadening were estimated to be smaller by more than an order of magnitude in comparison to Stark, Doppler, and instrumental broadening. The standard deconvolution procedure [35] was computerized using the least square algorithm. The Stark widths were measured with $\pm 15\%$ error. Great care was taken to minimize the influence of self-absorption on Stark width determinations. The opacity was checked by measuring relative line intensity ratios within the multiplet ^4P-$^4P^0$ in Kr II spectrum during the decaying plasma (465.89 nm and 483.21 nm). The values obtained were compared with calculated ratios of the products of the spontaneous emission probabilities and the corresponding statistical weights of the upper levels of the lines. The necessary atomic data were taken from Ref. [36]. It turns out that these ratios differed by less than $\pm 12\%$ (in a wide part of the decaying plasma, see Fig. 4) testing the absence of self-absorption. In the 20th μs after the beginnig of the discharge (when the profiles were analyzed) the theoretical ratio I_1/I_2 is only 10% above the experimental data. It should be pointed out that the experimental I_1/I_2 ratio is within $\pm 5\%$ accuracy constant during the plasma decay. This fact also shows the absence of self-absorption. The constant difference among measured and calculated line intensity ratios can be explained taking into account the high uncertainties ($\pm 50\%$) of the used transition probabilities [36].

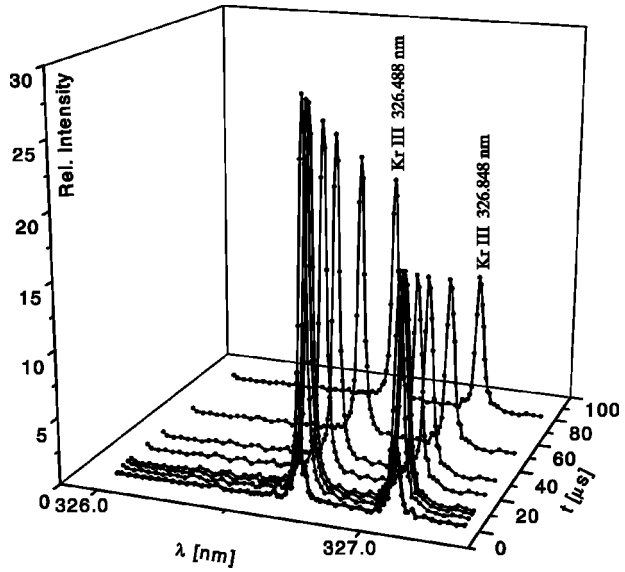

FIG. 2. Temporal evolution of several investigated Kr III spectral line profiles during the plasma decay.

The Stark shifts were measured relative to the unshifted spectral lines emitted by the same plasma [37]. The Stark shift of the spectral line can be measured experimentally by evaluating the position of the spectral line center recorded at two various electron density values during the plasma decay. In principle the method requires recording of the spectral line profile at the high electron density (N_1) that causes an appreciable shift, and then later when the electron concentration has dropped to the value (N_2) lower for at least an order of magnitude. The difference of the line center positions in the two cases is Δd, so that the shift d_1 at the higher electron density N_1 is

$$d_1 = N_1 \Delta d/(N_1 - N_2).$$

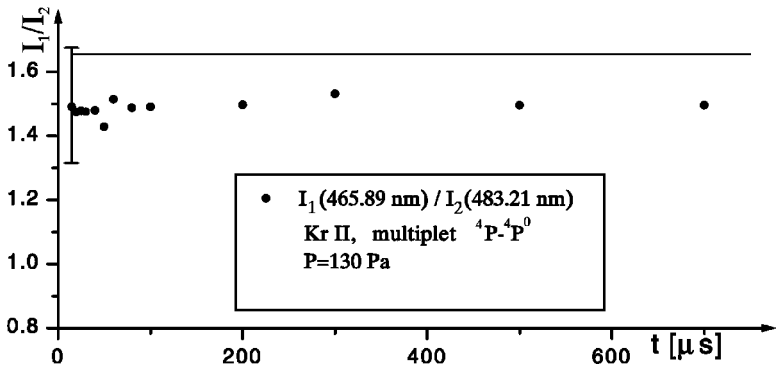

FIG. 4. Intensity ratio of two Kr II spectral lines belonging to the same multiplet during the plasma decay. —, theoretical prediction; ●, our measured values with ±12% accuracy.

The Stark shift data have been corrected for the electron temperature decay [38]. Stark shift data are determined with ±0.0008 nm error at a given N and T. The plasma parameters were determined using standard diagnostic methods [39]. Thus, the electron temperature was determined from the ratios of the relative intensities of nine Kr II spectral lines (435.547 nm, 457.720 nm, 461.529 nm, 461.915 nm, 463.388 nm, 465.887 nm, 473.900 nm, 476.577 nm, 483.207 nm) to the five Kr I spectral lines (435.136 nm, 436.264 nm, 446.369 nm, 557.028 nm, 587.091 nm) with an estimated error of ±9%, assuming the existence of local thermodynamic equilibrium, according to the criterion from Ref. [40]. All the necessary atomic data were taken from Refs. [36,41]. The electron temperature decay is presented in Fig. 5. The electron density decay was measured using a well known single laser interferometry technique [42] for the 632.8 nm He-Ne laser wavelength with an estimated error of ±7%. Temporal evolution of the typical interferometry signal is presented in Fig. 3. The electron density decay is presented, also, in Fig. 5.

At 20 μs after the beginning of the discharge, when the Kr II and Kr III spectral line profiles were analyzed, electron temperature was 17 000 K±9% and the electron density was 1.65×10^{23} m^{-3}±7%.

III. METHOD OF CALCULATION

According to the modified semiempirical (MSE) approach [17,20,26–31] the electron impact full width (FWHM) of an ion line is given as

$$W_{MSE}=N\frac{8\pi}{3}\frac{\hbar^2}{m^2}\left(\frac{2m}{\pi kT}\right)^{1/2}\frac{\pi}{\sqrt{3}}\times\left\{\sum_{\ell_i\pm1}\mathbf{R}^2[n_i\ell_i,n_i(\ell_i\pm1)]\tilde{g}\left(\frac{E}{\Delta E_{\ell_i,\ell_i\pm1}}\right)+\sum_{\ell_f\pm1}\mathbf{R}^2[n_f\ell_f,n_f(\ell_f\pm1)]\tilde{g}\left(\frac{E}{\Delta E_{\ell_f,\ell_f\pm1}}\right)+\left(\sum_{i'}\mathbf{R}^2_{ii'}\right)_{\Delta n\neq0}g(x_{n_i,n_i+1})+\left(\sum_{f'}\mathbf{R}^2_{ff'}\right)_{\Delta n\neq0}g(x_{n_f,n_f+1})\right\},\tag{1}$$

and the corresponding Stark shift as

$$d=N\frac{4\pi}{3}\frac{\hbar^2}{m^2}\left(\frac{2m}{\pi kT}\right)^{1/2}\frac{\pi}{\sqrt{3}}\left\{\varepsilon_{\ell_i,\ell_i+1}\mathbf{R}^2[n_i\ell_i,n_i(\ell_i+1)]\tilde{g}_{sh}\left(\frac{E}{\Delta E_{\ell_i,\ell_i+1}}\right)-\varepsilon_{\ell_i,\ell_i-1}\mathbf{R}^2[n_i\ell_i,n_i(\ell_i-1)]\tilde{g}_{sh}\left(\frac{E}{\Delta E_{\ell_i,\ell_i-1}}\right)-\varepsilon_{\ell_f,\ell_f+1}\mathbf{R}^2[n_f\ell_f,n_f(\ell_f+1)]\tilde{g}_{sh}\left(\frac{E}{\Delta E_{\ell_f,\ell_f+1}}\right)+\varepsilon_{\ell_f,\ell_f-1}\mathbf{R}^2[n_f\ell_f,n_f(\ell_f-1)]\tilde{g}_{sh}\left(\frac{E}{\Delta E_{\ell_f,\ell_f-1}}\right)+\left(\sum_{i'}\mathbf{R}^2_{ii'}\right)_{\Delta n\neq0}g_{sh}(x_{n_i},x_{n_i+1})-2\sum_{i'(\Delta E_{ii'}<0)}\mathbf{R}^2_{ii',\Delta n\neq0}g_{sh}\left(\frac{E}{\Delta E_{n_i,\ell_i,n_{i'}\ell_{i'}}}\right)-\left(\sum_{f'}\mathbf{R}^2_{ff'}\right)_{\Delta n\neq0}g_{sh}(x_{n_f},x_{n_f+1})+2\sum_{f'(\Delta E_{ff'}<0)}\mathbf{R}^2_{ii',\Delta n\neq0}g_{sh}\left(\frac{E}{\Delta E_{n_f,\ell_f,n_{f'}\ell_{f'}}}\right)+\sum_k\delta_k\right\},\tag{2}$$

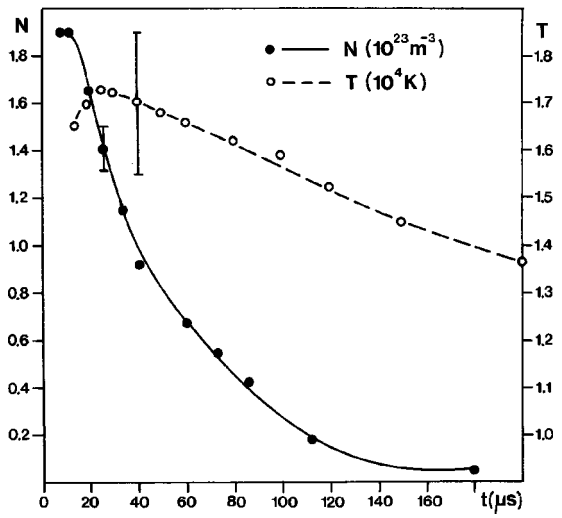

FIG. 5. Temporal evolution of the electron temperature (T) and electron density (N) during the plasma decay.

where the initial level is denoted with i and the final one with f and the square of the matrix element $\{\mathbf{R}^2[n_k\ell_k, n_k(\ell_k \pm 1)],\ k=i,f\}$ is

$$\mathbf{R}^2[n_k\ell_k, n_k(\ell_k\pm 1)] = \left(\frac{3n_k^*}{2Z}\right)^2 \frac{\ell_>}{2\ell_k+1} \times (n_k^{*2}-\ell_k^2)\Phi^2(n^{*2}_{\ell_k-1}, n^{*2}_{\ell_k}, \ell_k) \tag{3}$$

and

$$\left(\sum_{k'} \mathbf{R}^2_{kk'}\right)_{\Delta n\neq 0} = \left(\frac{3n_k^*}{2Z}\right)^2 \frac{1}{9}(n_k^{*2}+3\ell_k^2+3\ell_k+11), \tag{4}$$

where $\ell_> = \max(\ell_k, \ell_{k'})$, with ℓ denoting the angular momentum quantum number.

In Eqs. (1)–(4), N and T are electron density and temperature, respectively, and Φ is the Bates-Damgaard factor tabulated e.g., in Ref. [43]. Here, $g(x), g_{sh}(x)_{sh}$ and $\tilde{g}(x), \tilde{g}_{sh}(x)$ are the semiempirical [15] and the modified semiempirical [17,27] Gaunt factors for Stark width and shift, respectively. The factor $\varepsilon_{kk'} = (E_{k'}-E_k)/|E_{k'}-E_k|$, where E_k and $E_{k'}$ are the energy of the considered and its perturbing level. The sum $\Sigma_k \delta_k$ is different from zero only if perturbing levels strongly violating the assumed approximations exist and may be evaluated as

$$\delta_i = \pm \mathbf{R}^2_{ii'}\left[g_{sh}\left(\frac{E}{\Delta E_{i,i'}}\right) \mp g_{sh}(x_{n_i, n_i+1})\right], \tag{5}$$

for the upper level, and

$$\delta_f = \mp \mathbf{R}^2_{ff'}\left[g_{sh}\left(\frac{E}{\Delta E_{f,f'}}\right) \mp g_{sh}(x_{n_f, n_f+1})\right], \tag{6}$$

for the lower level. In Eqs. (5) and (6) lower signs correspond to $\Delta E_{jj'} < 0$; $x_{n_k, n_k+1} \approx 3kTn_k^{*3}/(2Z^2E_H)$, where $\Delta E_{kk'} = |E_k - E_{k'}|$, n_k is the principal, n_k^* the effective principal quantum number, $E = 3kT/2$, and $(Z-1)$ is the ionic charge.

In comparison with the semiclassical perturbation approach [40], the modified semiempirical method needs a considerably smaller number of atomic data. In fact, if there are no perturbing levels strongly violating the assumed approximation, for, e.g., the linewidth calculations, we need only the energy levels with $\Delta n = 0$ and $\ell_{if} = \ell_{if} \pm 1$, since all perturbing levels with $\Delta n \neq 0$ needed for a full semiclassical investigation are lumped together and approximately estimated. When there are not enough atomic data to perform calculations within the modified semiempirical approach, of particular interest might be the simplified semiempirical formula [20] for Stark widths of isolated, singly, and multiply charged ion lines applicable in the cases when the nearest atomic energy level ($j' = i'$ or f') where a dipole allowed transition can occur from or to initial (i) or final (f) energy level of the considered line, is so far, that the condition

$$x_{jj'} = E/|E_{j'} - E_j| \leqslant 2$$

is satisfied. In such a cases full width at half maximum is given by the expression [20]:

$$W(\text{nm}) = 2.2151 \times 10^{-9} \frac{\lambda^2(\text{cm}) N(\text{cm}^{-3})}{T^{1/2}(\text{K})}\left(0.9 - \frac{1.1}{Z}\right) \times \sum_{\text{j = i,f}} \left(\frac{3n_j^*}{2Z}\right)^2 (n_j^{*2} - \ell_j^2 - \ell - 1). \tag{7}$$

Similarly, in the case of the shift

$$d(\text{nm}) = 1.1076 \times 10^{-9} \frac{\lambda^2(\text{cm}) N(\text{cm}^{-3})}{T^{1/2}(\text{K})}\left(0.9 - \frac{1.1}{Z}\right) \times \frac{9}{4Z^2} \sum_{j=i,f} \frac{n_j^* \varepsilon_j^2}{2\ell_j+1}\{(\ell_j+1)[n_j^{*2} - (\ell_j+1)^2] - \ell_j(n_j^{*2} - \ell_j^2)\}, \tag{8}$$

where $\varepsilon = +1$ if $j = i$ and -1 if $j = f$.

If all levels $\ell_{i,f} \pm 1$ exist, an additional summation may be performed in Eq. (8) to obtain

$$d(\text{nm}) = 1.1076 \times 10^{-9} \frac{\lambda^2(\text{cm}) N(\text{cm}^{-3})}{T^{1/2}(\text{K})} \times \left(0.9 - \frac{1.1}{Z}\right) \frac{9}{4Z^2} \sum_{j=i,f} \frac{n_j^* \varepsilon_j^2}{2\ell_j+1} \times (n_j^{*2} - 3\ell_j^2 - 3\ell_j - 1). \tag{9}$$

In order to test the modified semiempirical approach, selected experimental data for 36 multiplets (7 different ion species) of doubly charged ions and 7 multiplets (4 different ion species) of triply charged ions were compared with theoretical results. The averaged values of the ratios of mea-

TABLE I. Measured Stark FWHM (W_m) and shift (d_m) values for the Kr II and Kr III lines at an observed electron temperature (T) of 17 000 K and electron density (N) of 1.65×10^{23} m^{-3}. W_m/W_{th} presents the ratio between our mesured (W_m) and calculated (W_{th}) values (from Ref. [16] and from Tables II–IV). An asterisk denotes the W_{th} values taken from Ref. [16]. + denotes the W_{th} values calculated by using the simplified semiempirical method. Positive shift is toward the red.

Emitter	Transition	Multiplet	λ (nm)	W_m (nm)	d_m (nm)	W_m/W_{th}
Kr II	$5s$-$5p$	$^4P_{5/2}$-$^4P^0_{3/2}$	465.89	0.0399	−0.0010	0.90*
		$^4P_{3/2}$-$^4P^0_{1/2}$	483.21	0.0429	−0.0014	0.84*
		$^4P_{5/2}$-$^4D^0_{7/2}$	435.55	0.0378	−0.00	0.95*
		$^4P_{5/2}$-$^4D^0_{5/2}$	473.90	0.0338	−0.0014	0.73*
		$^4P_{3/2}$-$^4D^0_{5/2}$	476.57	0.0454	−0.00	0.92*
		$^2P_{3/2}$-$^2P^0_{1/2}$	484.66	0.0426	−0.00	0.89*
		$^2P_{3/2}$-$^2P^0_{3/2}$	461.53	0.0454	−0.00	1.05*
		$^2P_{3/2}$-$^2D^0_{5/2}$	461.91	0.0305	−0.00	0.74*
	$5s'$-$5p'$	$^2D_{3/2}$-$^2F^0_{5/2}$	463.39	0.0391	−0.0018	0.64*
		$^2D_{5/2}$-$^2F^0_{7/2}$	457.72	0.0449	−0.00	1.00*
		$^2D_{5/2}$-$^2P^0_{3/2}$	447.50	0.0512	−0.0017	1.03*
		$^2D_{5/2}$-$^2D^0_{5/2}$	408.83	0.0274	−0.0017	0.79*
	$5p$-$5d$	$^4D^0_{7/2}$-$^4F_{9/2}$	378.31	0.0879		0.83
		$^4D^0_{5/2}$-$^4F_{7/2}$	377.81	0.0848	0.0090	0.79
Kr III	$5s$-$5p$	$^5S^0_2$-$^5P_1$	335.19	0.0308	0.0032	1.09
		$^5S^0_2$-$^5P_2$	332.58	0.0290	0.0031	1.04
		$^5S^0_2$-$^5P_3$	324.57	0.0300	0.0026	1.13
		$^3S^0_1$-$^3P_2$	350.74	0.0328	0.0020	0.99
	$5s'$-$5p'$	$^3D^0_2$-$^3D_2$	343.95	0.0306	0.0021	1.01
		$^3D^0_1$-$^3F_2$	326.85	0.0261		1.12
		$^3D^0_3$-$^3F_4$	326.49	0.0214	0.0015	0.92
		$^3D^0_3$-$^3P_2$	302.44	0.0280	0.0011	0.91
	$5s''$-$5p''$	$^3P^0_2$-$^3D_3$	337.49	0.0480	0.0013	1.44^+
		$^3P^0_2$-$^3P_2$	304.69	0.0395	0.00	1.46^+
	$4d''$-$5p''$	$^3D^0_2$-$^3D_3$	302.23	0.0455	0.00	

sured to calculated widths are as follows [17]: for doubly charged ions 1.06 ± 0.32 and for triply charged ions 0.91 ± 0.42. The modified semiempirical approach has been tested several times on numerous examples (see, e.g., Ref. [44]).

In Ref. [16] Stark widths of 37 Kr II lines that belong to the $5s$-$5p$ and $5s'$-$5p'$ transitions have been calculated within the frame of the modified semiempirical approach. We present here the results of the Stark shift calculations for 12 Kr II lines that belong to the $5s$-$5p$ and $5s'$-$5p'$ transitions. The needed atomic energy levels have been taken from Ref. [45]. Moreover, we present here the results for Stark widths and shifts obtained within the modified semiempirical approach for two lines that belong to the Kr II $5p^4D$-$5d^4F^o$ multiplet. For these lines $5f$ levels are not in the LS coupling but we took them together within the one electron approximation (see, e.g., Ref. [40]).

The needed atomic energy levels for Kr III have been taken from Ref. [45] as for Kr II. We present here the results of the Stark widths (FWHM) and shifts calculations within the frame of the modified semiempirical approach for 5 Kr III multiplets. In the case of Kr II $5s'^3D^o$-$5p'^3F$ and the $5s'^3D^o$-$5p'^3P$ multiplets $5d'$ energy levels needed for calculations are incomplete and they do not have the LS coupling designations. We have taken $5d'$ levels within the one electron approximation with the energy of 237 970.03 cm^{-1}. The Kr III $5s''^3P^o$-$5p''^3D$ and $5s''^3P^o$-$5p''^3P$ multiplets may be treated only within the simplified modified semiempirical method [20] [Eqs. (7)–(9)], since there is not enough atomic energy level data for the full modified semiempirical calculation. Consequently, the corresponding calculation has been performed.

IV. RESULTS

The results of the measured Stark FWHM (W_m) and shift (d_m) values at $T=17\,000$ K electron temperature and 1.65×10^{23} m^{-3} electron density are shown in Table I. Ratios W_m/W_{th} are also given, where W_{th} is the Stark FWHM calculated within the modified semiempirical approach by us and from Ref. [16].

Stark shift values (d) calculated by using the modified semiempirical method [Eqs. (1)–(6)] [17,27], for the Kr II lines at an electron density of 10^{23} m^{-3}, are presented in Table II, together with the Stark FWHM values (W) calculated for the lines that belong to the $5p$-$5d$ transition.

Stark FWHM (W) and shift (d) values calculated by using the modified semiempirical method [Eqs. (1)–(6)] [17,27], for the Kr III multiplets at 10^{23} m^{-3} electron density, are presented in Table III.

TABLE II. Stark shift values (d in nm) calculated by using the modified semiempirical method [Eqs. (1)–(6)] [17,27] for the Kr II spectral lines, at 10^{23} m^{-3} electron density. The Stark FWHM values (W in nm) are also given for the lines that belong to the $5p$-$5d$ transition.

		$T(10^4$ K)				
λ (nm)		1	2	3	4	5
473.90	d	−0.0101	−0.0074	−0.0063	−0.0058	−0.0056
465.89	d	−0.0111	−0.0082	−0.0070	−0.0064	−0.0062
483.21	d	−0.0111	−0.0082	−0.0070	−0.0064	−0.0062
435.55	d	−0.0083	−0.0061	−0.0051	−0.0047	−0.0044
476.53	d	−0.0089	−0.0066	−0.0056	−0.0051	−0.0049
484.66	d	−0.0125	−0.0092	−0.0078	−0.0071	−0.0069
461.53	d	−0.0104	−0.0076	−0.0064	−0.0058	−0.0055
461.91	d	−0.0099	−0.0073	−0.0061	−0.0055	−0.0052
463.39	d	−0.0056	−0.0036	−0.0029	−0.0029	−0.0028
457.72	d	−0.0091	−0.0066	−0.0056	−0.0051	−0.0049
447.50	d	−0.0103	−0.0071	−0.0057	−0.0051	−0.0049
408.83	d	−0.0065	−0.0047	−0.0039	−0.0035	−0.0033
378.31	W	0.0743	0.0624	0.0586	0.0567	0.0559
	d	0.0057	0.0108	0.0134	0.0149	0.0154
377.81	W	0.0749	0.0638	0.0599	0.0581	0.0572
	d	0.0076	0.0128	0.0155	0.0168	0.0172

Stark FWHM values calculated by using the simplified modified semiempirical method [20] [Eqs. (7)–(9)] for the Kr III multiplets at 10^{23} m^{-3} electron density are presented in Table IV.

V. DISCUSSION

In order to make the comparison easier between measured and calculated Stark width values, the theoretical Stark FWHM dependence on the electron temperature together with the values of the other authors and our experimental results at an electron density of 1×10^{23} m^{-3} are presented graphically in Figs. 6 and 7.

On the basis of the Table I, Table II, and Fig. 6 one can conclude that the comparison between our measured Stark FWHM values of the Kr II lines with the theoretical predictions from Ref. [16] show a satisfactory agreement taking into account that the assumed error bars of the modified semiempirical method are ±50% [17]. Generally, our W_m values lie below the theoretical up to −13% in average (see W_m/W_{th}, values in Table I). It should be pointed out that our new W_m values at 17 000 K electron temperature agree

TABLE III. Stark FWHM (W) and shift (d) values (in nm) calculated by using the modified semiempirical method [Eqs. (1)–(6)] [17,27] for the Kr III spectral lines, at 10^{23} m^{-3} electron density. $\overline{\lambda}$ is the mean wavelength of the multiplet.

Transition		$T(10^4$ K)						
$\overline{\lambda}$ (nm)		1	2	3	4	5	6	7
$5s^5S^o$-$5p^5P$								
329.394	W	0.0212	0.0148	0.0120	0.0104	0.0094	0.0087	0.0083
	d	−0.0033	−0.0024	−0.0020	−0.0016	−0.0015	−0.0014	−0.0013
$5s^3S^o$-$5p^3P$								
352.504	W	0.0261	0.0182	0.0148	0.0129	0.0117	0.0109	0.0103
	d	−0.0044	−0.0032	−0.0025	−0.0022	−0.0020	−0.0018	−0.0017
$5s'^3D^o$-$5p'^5D$								
335.996	W	0.0201	0.0140	0.0114	0.0099	0.0089	0.0083	0.0078
	d	−0.0074	−0.0058	−0.0051	−0.0047	−0.0045	−0.0044	−0.0042
$5s'^3D^o$-$5p'^3F$								
331.936	W	0.0191	0.0133	0.0108	0.0094	0.0085	0.0079	0.0074
	d	−0.0068	−0.0050	−0.0041	−0.0035	−0.0032	−0.0030	−0.0028
$5s'^3D^o$-$5p'^3P$								
292.412	W	0.0194	0.0135	0.0110	0.0095	0.0086	0.0080	0.0075
	d	−0.0057	−0.0044	−0.0039	−0.0038	−0.0037	−0.0036	−0.0037

TABLE IV. Stark FWHM values (in nm) calculated by using the simplified modified semiempirical method [Eqs. (7)–(9)] [20]. For the Kr III spectral lines, at 10^{23} m^{-3} electron density. $\overline{\lambda}$ is the mean wavelength for the multiplet.

Transition	$T(10^4$ K)				
$\overline{\lambda}$ (nm)	1	2	3	4	5
$5s''^3P^o$-$5p''^3D$					
338.647	0.0262	0.0185	0.0151	0.0131	0.0117
$5s''^3P^o$-$5p''^3P$					
311.773	0.0229	0.0162	0.0132	0.0115	0.0102
$4d''^3D^o$-$5p''^3D$					
279.607	0.00849	0.00600	0.00490	0.00425	0.00380

well with those from Ref. [10]. In the case of the Kr III spectral lines (see Table I, Table III, and Fig. 7) one can conclude that our measured (W_m) and calculated (W_{th}) values show very good mutual agreement (W_m/W_{th} ratios in Table I). Absence of the knowledge of the complete set of perturbing energy levels in the case of the $5s''$-$5p''$ and $4d''$-$5p''$ transitions make the calculations of W values possible only within the frame of the simplified semiempirical method [20]. Experimental Stark FWHM values from Ref. [18] agree with our calculated values (and with those from Ref. [23]) within a few percent. Contrarily, the measured W values from Ref. [19] lie above our (and Ref. [23]) results (see the $^5S^o$-^5P multiplet Fig. 7), especially around the electron temperature of 40 000 K, up to factor 2. It should be pointed out that the theoretical W values [24], calculated by using the quasiclassical Gaunt factor method [46,47], show agreement with our calculations. Calculations in Ref. [24] have been performed only for the plasma conditions for experiments in Ref. [19] and the results are given only for electron temperatures higher than 37 000 K. The possible reasons for disagreement between measurements from Ref. [19] and calculations from Ref. [24] are discussed in detail in Ref. [19].

In the case of the Stark shift the situation is much different. Generally, we have measured very small d_m values in the case of the Kr II and Kr III lines (see Table I). Within the accuracy of measurements (0.0008 nm) many of them were equal to zero. Our calculations give higher absolute d values than measured ones. Our calculated and measured Stark shift values, in the case of the Kr II lines (Table I and Table II), have the same sign. For the lines that belong to the $5s$-$5p$ and $5s'$-$5p'$ transitions d is negative and for lines from the $5p$-$5d$ transition d is positive. Our measured d_m values confirm the observed negative sign from Ref. [10] for three Kr II lines (473.90 nm, 465.89 nm, and 435.55 nm). Evident Stark shift, in our measurements, was observed only for the 377.81 nm Kr II line that belongs to the higher lying $5p$-$5d$ transition. In all cases shift values are considerably smaller than width ones. This indicates that particular important contributions have different sign and that their mutual cancellation occurs resulting in shifts much smaller than widths. Since the assumed accuracy of the method is $\pm 50\%$ of the width value, the reliability of these small shifts is much lower. Consequently, d_m/d_{th} ratios are not presented in this paper.

In the case of the Kr III lines our measured and calculated Stark shift values show different signs. Calculations give negative d values while the measured shifts are positive. One can see in Table III that shifts of the considered Kr III spectral lines are almost an order of magnitude smaller than the corresponding widths. Consequently, the mutual cancellations of important contributions are so significant that error bars of such results which might be an upper limit around 50% of the width value are extended to the positive shift values, too. Theoretical reasons for the discrepancies between the signs of measured and calculated Kr III shifts could be the consequence of the complexity of the Kr III many electron atom and its spectrum where the neglected optically forbidden transitions might have an important influence.

VI. CONCLUSION

We have presented in this paper experimental Stark widths and shifts for 14 Kr II and 11 Kr III spectral lines at an electron temperature of 17 000 K and an electron density of 1.65×10^{23} m^{-3}. Our results present the Kr III Stark line shift determination, and our work shows the second experimental result of reliable Kr II Stark line shifts. Moreover, we have calculated 14 Kr II Stark line shifts and 2 Kr II Stark linewidths within the frame of the modified semiempirical method. We have also presented the results of calculations by using the modified semiempirical approach of Stark widths and shifts for 5 Kr III multiplets and such results for 3 Kr III multiplets by using the simplified modified semiempirical method. Our results have been compared with other experimental and theoretical results.

We hope the obtained results will be of help not only for laboratory plasma diagnostics and krypton plasma research and modeling, but also (especially by using space borne telescopes and instruments such as the Goddard high resolution spectrograph on the Hubble space telescope), for the analysis of the trace element spectral lines and abundances. Such data may be of interest as well for the investigation of regularities within homologous noble gas ion sequences, and for examination of possibilities to use such regularities for the interpolation of new data.

One should emphasize here that all reliable experimental data for Kr II spectral lines are within a narrow temperature range between 10 000 and 17 400 K, where Stark widths decrease quicker than for higher temperatures. In order to check the theoretical temperature dependence it is of interest

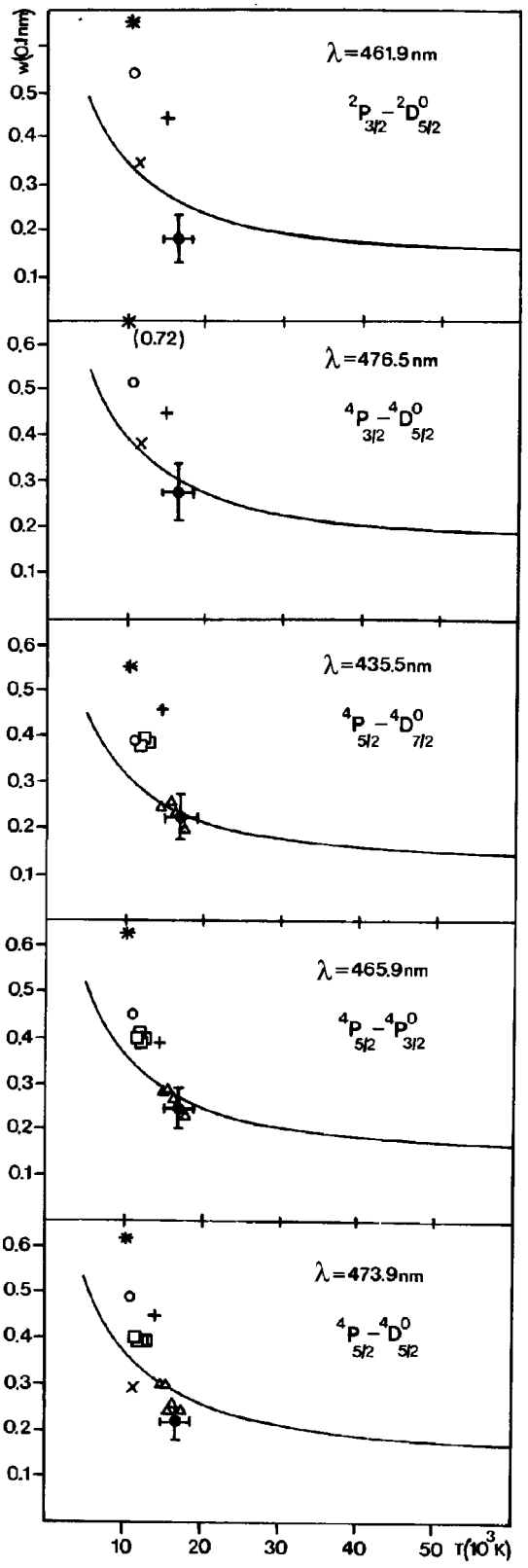

FIG. 6. Stark FWHM (W) dependence on the electron temperature for the most investigated Kr II spectral lines belonging to the $5s$-$5p$ transition at 1×10^{23} m^{-3} electron density. —, calculations by using the modifed semiempirical approach [16]. ● our experimental results and those of other authors: ×, Ref. [7]; *, Ref. [8]; △, Ref. [10]; □, Ref. [11]; ○, Ref. [12] and +, Ref. [13]. The error bars include the uncertainties of the width, electron density, and temperature measurements.

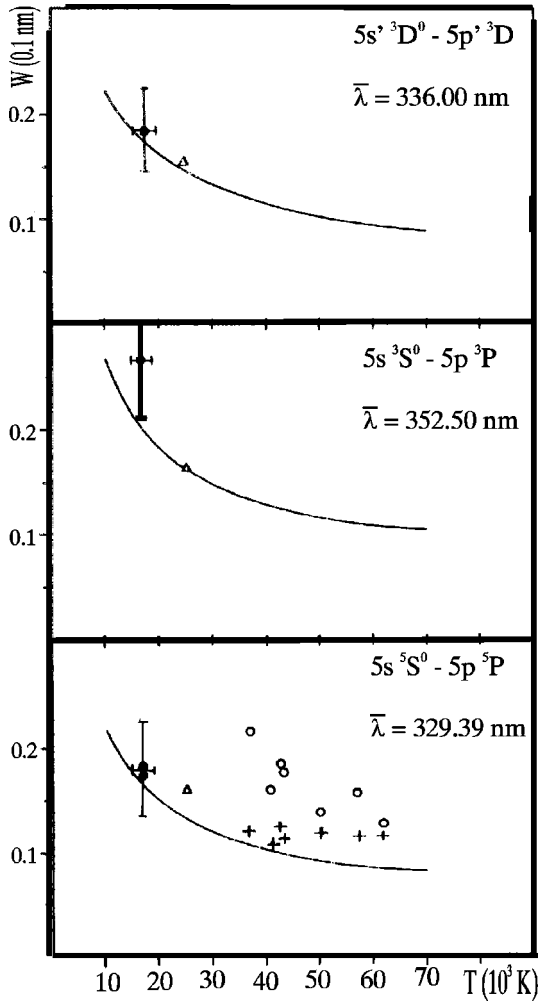

FIG. 7. Stark FWHM (W) dependence on the electron temperature for the most investigated Kr III spectral lines belonging to the $5s$-$5p$ and $5s'$-$5p'$ transition at 1×10^{23} m^{-3} electron density. —, our calculations by using the modifed semiempirical approach. ●, our experimental results and those of other authors: △, Ref. [18] and ○, Ref. [19]. +, calculations by using the quasiclassical Gaunt factor method [24] performed only for the plasma parameters observed in the experiment in Ref. [19]. The error bars include the uncertainties of the width, electron density, and temperature measurements.

to perform reliable experimental determinations on higher temperatures. It is of interest also to perform high precision measurements of Stark widths within the Kr III $5s^5S^o$-$5p^5P$ multiplet, where three experimental results within a wide temperature range exist. For this multiplet it is of interest to perform calculations of higher precision than here, when new atomic energy level data become available.

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