Stark widths and shifts of neutral neon spectral lines

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The neon spectrum is of considerable laser-physics interest, yet few measurements of its spectral line broadening and shift parameters have been performed. In this investigation the Stark widths and shifts of twenty Ne I lines originating from several multiplets were measured as functions of electron density and temperature in the ranges $(0.15-1.40)\times10^{23}$ m^{-3} and $(1-2.5)\times10^{4}$ K, respectively. The light source was the plasma of an electromagnetically driven "T tube" operating in a mixture of neon and argon in the ratio 2:5 in order to avoid self-absorption. The electron density was measured by single-wavelength laser interferometry using the visible $\lambda=632.8$ nm transition of a He-Ne laser, and the electron temperature from the Boltzmann slope of several Ar II spectral lines with estimated errors of $\pm7\%$ and $\pm10\%$, respectively. The obtained measured Stark widths (w) and shifts (d) with estimated errors of $\pm15\%$ are compared with the existing experimental and theoretical data. All together, Stark widths and shifts data are used to demonstrate the nature of Stark broadening and shift dependence on the upper-level ionization potential of the corresponding line in a transition array.

I. INTRODUCTION

Several papers deal with the experimental determination of Stark broadening and shift parameters of neutral-neon spectral lines.[1–4] In all cases the comparison was done with Griem's theoretical results.[5] It was found that the agreement between the obtained experimental results and theory is within $\pm15\%$ and between the various experiments within $\pm20\%$. The aim of this work is to supply more experimental data by a systematic measurement of the Stark widths and shifts of twenty spectral lines in relatively large ranges of electron temperature and density.

A majority of the investigated spectral lines originates from the following transition array: $3s$-$3p$. Therefore, it was possible to discuss the Stark width and shift dependence on the upper-level ionization potential of the corresponding line proposed by Purić, Ćuk, and Lakićević.[6,7] The obtained trends using Griem's theoretical data and present results are in a very good accordance with the expected functional dependence of the form

$$w=a_1 I^{-b_1}, \tag{1}$$

$$d=a_2 I^{-b_2}, \tag{2}$$

where a_1, b_1, a_2, and b_2 are coefficients independent of the ionization potential I.

II. EXPERIMENT

An electromagnetic shock T tube was used as a plasma source during the course of this experiment. The experimental apparatus used was described elsewhere[7,8] and only a few details are given here for the sake of completeness. The working gas was a mixture of neon and argon in the ratio 2:5 in order to avoid self-absorption. The experiment was carried out at 66.7 Pa gas pressure and the discharge was driven by a 7.5-μF condenser bank charged to 15 kV. All observations were done at the position of 12 mm from the reflector and 15 cm from the electrodes. Special care was paid to minimize the influence of self-absorption on the Stark width measurement. The optical depth was checked by measuring line-intensity ratios within a multiplet. Measured values were compared with calculated ratios (according to Jl coupling) of the products of the spontaneous-transition probabilities and the corresponding statistical weights of their upper levels. These ratios were found to be the same up to $\pm10\%$ within each multiplet. The reproducibility of the plasma was controlled continuously during the course of the experiment by measuring the intensity of continuum radiation at a chosen wavelength (λ is less than the blue wing of 632.8-nm Ne I line) and was found to be within $\pm10\%$.

The electron temperature was determined from the Boltzmann slope of several Ar II spectral lines with estimated errors up to $\pm10\%$. Five temperatures (10 000, 12 000, 16 000, 20 000, and 25 000 K) were chosen during the plasma decay and at those instants spectral lines were analyzed. The electron densities were determined by single-wavelength laser interferometry using the visible transition of a He-Ne laser with 7% precision. For the given conditions the electron density was in the range of $(0.15-1.40)\times10^{23}$ m^{-3}. The light from the shock tube was observed by a photomultiplier (EMI 9659B) grating spectrograph (Zeiss PGS-2, inverse linear dispersion in first order 0.735 nm/mm) system whose output was displayed on a double-beam oscilloscope and photo-

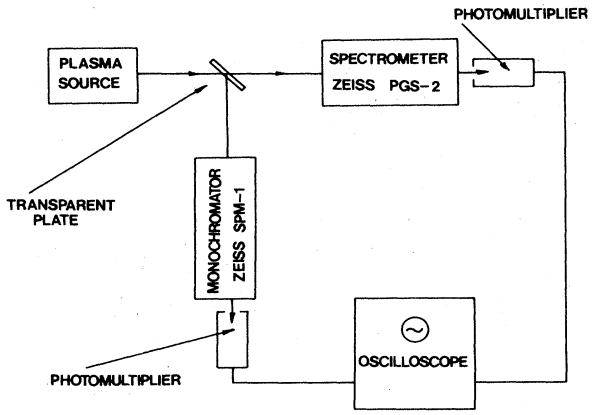

FIG. 1. Schematic diagram of the apparatus.

graphed for analysis (Fig. 1). Another monochromator system (Zeiss SPM-1) with photomultiplier was used simultaneously to monitor the continuum radiation from the same part of the plasma to check the reproductibility. The scanning of the spectral lines was done by a shot-by-shot technique advancing the exit slit photomultiplier combination in small wavelength steps. Shifts were measured relative to unshifted lines emitted by the same plasma observed at a later time at lower electron densities during the decay.[9] A majority of the obtained spectral-line profiles were of the Voigt type as the convolution of the dispersion Stark profile and the Gaussian profile due to instrumental and Doppler broadening. In this work, due to the special experimental conditions, only instrumental and Doppler broadening were considered as competing fractions in comparison with the Stark broadening in the total line width. van der Waals and resonance broadening were ignored. To get the dispersion component of the profile from the obtained experimental profile, i.e., Voigt profile, deconvolution was performed by the standard procedure.[10]

III. RESULTS AND DISCUSSION

Stark widths for all the investigated neutral-neon spectral lines are determined in nm units and normalized to 10^{23} m^{-3} electron density. The measured Stark half width at half maximum (HWHM) w_m (nm) are presented in Table I together with theoretical and experimental values of Stark HWHM of other authors at different electron temperatures. The linear dependence of Stark HWHM on electron concentration of Ne I spectral lines of multiplets (1, 1′, 3, 3′, 5′, 6, 6′, and 12) is found. For the sake of better comparison, theoretical values of Stark HWHM have to be renormalized to the corresponding electron concentrations and same temperature when presented graphically. Measured HWHM are generally in good agreement with the calculated ones[5] within the experimental error of the order of $\pm 15\%$. The best agreement is obtained at 20 000 K which is as expected since the corresponding electron density is maximum (1.4×10^{23} m^{-3}), i.e., Stark HWHM are determined more correctly (with less error). In some cases larger disagreement at the later time exists (up to 30%), when the electron concentration is about six times less than the maximum value. The disagreement can be due to the error in measuring electron concentration, and self-absorption may also be the cause for this disagreement. In general, measured values of Stark widths in this work are higher than the theoretically predicted values[5] and experimental results[1,2] at lower temperatures. The greatest disagreement between measured values and theoretical values of Griem[5] is for multiplet no. 6 where measured values are smaller than the theoretical values. Similarly, measured values are less than theoretical values for multiplet no. 3 and for the Ne I 748.89-nm line. Disagreement within one multiplet Stark width data is due to differences in upper-level excitation energies and can be explained on the basis of Stark width dependence on the upper-level ionization potential. A weak temperature dependence of Stark widths of investigated multiplets has been found as predicted by theory.

In this work Stark shifts of neutral-neon spectral lines are determined more correctly than Stark HWHM; as in the case of shifts, there is not other disturbing factor, except a small dependence of shifts on electron temperature. Almost all the studied spectral lines have shown considerable positive shifts. The shifts of all measured neutral-neon spectral lines were determined by the method which is clearly illustrated by Fig. 2. In the figure two line profiles of Ne I 594.48-nm line at the maximum electron concentration 1.4×10^{23} m^{-3} (relatively shifted) and 40 μs later at an electron concentration less than 0.01×10^{23} m^{-3} (relatively unshifted) are shown. From Fig. 2 the relative shift between the maxima of the two line profiles can easily be determined in wavelength units. In a similar way shifts of all above-mentioned neutral-neon spectral lines were determined. All the obtained values of Stark shifts normalized to 10^{23} m^{-3} electron concentration and averaged by the least-square method are presented in Table II, together with theoretical prediction[5] and previously published experimental data.[2] A linear dependence of the Stark shifts on electron concentration is found for all Ne I spectral lines of multiplets (1, 1′, 3, 3′, 5′, 6, 6′, and 12) as demanded by the theory. For the sake of better comparison, theoretically calculated values have to be renormalized to the corresponding electron concentration when they are presented graphically as in the case of Stark HWHM.

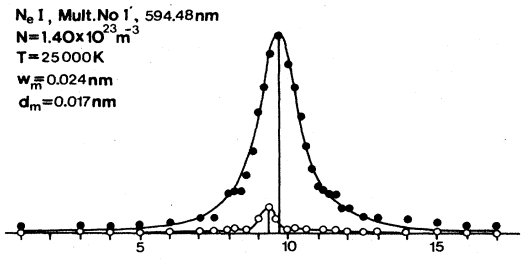

FIG. 2. Two Ne I 594.48-nm line profiles at $N=1.40\times10^{23}$ m^{-3} (●) and $N=0.01\times10^{23}$ m^{-3} (○).

TABLE I. Measured Stark HWHM w_m (nm) of Ne I lines normalized to 10^{23} m^{-3} electron density compared with theoretical w^5_{theor} and experimental w^1_{expt} values at various electron temperatures.

$N=10^{23}$ m^{-3}		T (K)	25 000		20 000			16 000		12 000			10 000		
Transition array	Mult. no.	λ (nm)	w_m	w_{theor}	w_m	w_{theor}	w_m/w_{theor}	w_m	w_{theor}	w_m	w_{theor}	w_{expt}	w_m	w_{theor}	w_{expt}
$2p^5 3s$-$2p^5(^2P^\circ_{3/2})3p$	(1)	640.22	0.033	0.028	0.037	0.0258	1.430	0.050	0.0225	0.040	0.0206	0.020	0.045	0.0194	0.022
		621.73	0.023		0.026		1.007	0.027		0.025			0.044		
		633.44	0.026		0.024		0.930	0.032		0.035		0.015	0.042		0.0152
		614.31	0.027		0.0253		0.980	0.030		0.022		0.019	0.045		0.023
		703.24	0.030	0.0292	0.027	0.0267	1.010	0.034	0.0245	0.048	0.022		0.048	0.0186	
$2p^5(^2P^\circ_{3/2})3s$-$2p^5(^2P^\circ_{1/2})3p'$	(1′)	594.48	0.024	0.0248	0.023	0.0231	0.990	0.025	0.0215	0.030	0.019	0.018	0.026	0.018	0.016
		588.19	0.023		0.024		1.038	0.025		0.027		0.016	0.040		0.0165
$2p^5 3s$-$2p^5(^2P^\circ_{3/2})3p$	(3)	650.65		0.029		0.027			0.024		0.022			0.202	
		607.43	0.023		0.024		0.888	0.025		0.027		0.016	0.040		0.0165
		638.30	0.025		0.030		1.111	0.025		0.035		0.017	0.035		0.0172
		724.52	0.028	0.032	0.031	0.0291	1.030	0.038	0.026	0.036	0.0235		0.045	0.020	
$2p^5(^2P^\circ_{3/2})3s$-$2p^5(^2P^\circ_{1/2})3p'$	(3′)	609.62	0.022	0.026	0.025	0.024	1.024	0.025	0.0216	0.027	0.020	0.018	0.035	0.0188	0.019
		603.00	0.025		0.026		1.065	0.025		0.025			0.040		
		540.00	0.027		0.0234		0.960	0.030		0.032			0.035		
$2p^5 3s'$-$2p^5(^2P^\circ_{1/2})3p'$	(5′)	626.65	0.025	0.0294	0.023	0.0257	0.894	0.030	0.0225	0.036	0.021	0.013	0.039	0.0198	0.0135
		616.36	0.026		0.023		0.894	0.030		0.036		0.012	0.040		0.012
$2p^5(^2p^\circ_{1/2})3s'$-$2p^5(^2P^\circ_{1/2})3p$	(5′)	692.95		0.036		0.0333			0.029		0.026			0.024	
		717.39	0.026		0.030		0.090	0.033		0.043			0.045		
		702.42	0.0225		0.021		0.630	0.026		0.029			0.037		
$2p^5 3s'$-$2p^5(^2P^\circ_{1/2})3p'$	(6′)	667.83		0.033		0.0298			0.028		0.024			0.0215	
		585.25	0.030		0.033		1.107	0.040		0.043		0.035	0.047		0.045
$2p^5 3p$-$2p^5(^2P^\circ_{3/2})3d$		748.89	0.186	0.225	0.193	0.223	0.865	0.210	0.220	0.232	0.215		0.220	0.208	
$2p^5 3p$-$2p^5(^2P^\circ_{3/2})3d$	(12)	837.76	0.267	0.255	0.265	0.245	1.080	0.240	0.235	0.255	0.225		0.255	0.220	

TABLE II. Measured Stark shift d (nm) of Ne I lines normalized to 10^{23} m^{-3} electron density compared with theoretical w^5_{theor} and experimental w^1_{expt} values at various electron temperatures. (A positive shift is a red shift.)

$N=10^{23}$ m^{-3}		T (K)	25 000		20 000			16 000		12 000		10 000			11 650
Transition array	Mult. no.	λ (nm)	d_m	d_{theor}	d_m	d_{theor}	d_m/d_{theor}	d_m	d_{theor}	d_m	d_{theor}	d_m	d_{theor}	d_m/d_{theor}	d_{expt}
$2p^5 3s$-$2p^5(^2P^\circ_{3/2})3p$	(1)	640.22	0.0132	0.0160	0.0160	0.0164	0.975	0.020	0.017	0.020	0.0168	0.017	0.0167	0.018	
		621.73	0.0125		0.0125		0.762	0.014		0.011		0.12		0.718	
		633.44	0.0133		0.014		0.850	0.014		0.0138		0.010		0.598	
		614.31	0.0227		0.022		1.340	0.025		0.027		0.024		1.437	
		703.24	0.007	0.0055	0.008	0.0063	1.270	0.007	0.007	0.010	0.007	0.009	0.0069	1.300	
$2p^5(^2P^\circ_{3/2})3s$-$2p^5(^2P^\circ_{1/2})3p'$	(1′)	594.48	0.0170	0.0175	0.018	0.0178	1.011	0.0182	0.0176	0.0155	0.0177	0.0170	0.0178	0.955	
		588.19	0.0150		0.015		0.842	0.0154		0.019		0.015		0.840	
$2p^5 3s$-$2p^5(^2P^\circ_{3/2})3p$	(3)	650.65		0.015		0.0164			0.017		0.0167		0.0168		0.023
		607.43	0.014		0.014		0.853	0.0138		0.022		0.012		0.714	
		638.30	0.018		0.017		1.036	0.020		0.020		0.024		1.420	
		724.52	0.008	0.0035	0.007	0.0037	1.890	0.012	0.004	0.009	0.0042		0.009	0.042	
$2p^5(^2P^\circ_{3/2})3s$-$2p^5(^2P^\circ_{1/2})3p'$	(3′)	609.62	0.0166	0.0168	0.017	0.0176	0.965	0.016	0.0175	0.014	0.0175	0.013	0.0176	0.738	
		603.00	0.016		0.018		1.022	0.020		0.018		0.014		0.795	
		540.00	0.022		0.022		1.250	0.030		0.034		0.027		1.530	
$2p^5 3s'$-$2p^5(^2P^\circ_{1/2})3p'$	(5′)	626.65	0.0174	0.018	0.017	0.0185	0.920	0.0187	0.019	0.018	0.0187	0.016	0.0186	0.860	
		616.36	0.020		0.022		1.200	0.018		0.025		0.032		1.720	
$2p^5(^2p^\circ_{1/2})3s'$-$2p^5(^2P^\circ_{1/2})3p$	(6)	692.95		0.0125		0.0126			0.0132		0.0135		0.0138		0.027
		717.39	0.0163		0.015		1.200	0.020		0.024		0.021		1.520	
		702.42	0.0135		0.014		1.111	0.017		0.0086		0.012		0.869	
$2p^5 3s'$-$2p^5(^2P^\circ_{1/2})3p'$	(6′)	667.83		0.012		0.0124			0.013		0.0133		0.0135		0.025
		585.25	0.025		0.024		1.930	0.025		0.024		0.023	1.700		
$2p^5 3p$-$2p^5(^2P^\circ_{3/2})3d$		748.89	0.198	0.189	0.179	0.195	0.918	0.165	0.200	0.160	0.206	0.170	0.210	0.809	
$2p^5 3p$-$2p^5(^2P^\circ_{3/2})3d$	(12)	837.76	0.160	0.210	0.164	0.213	0.770	0.174	0.220	0.150	0.224	0.150	0.227	0.660	

Measured shift values are, generally, in good agreement with the calculated ones,[5] within the experimental error of ±15% and theoretical uncertainty of ±10%. The best agreement is obtained at 20 000 K, which is expected, since the corresponding electron concentration is maximum, i.e., Stark shifts are determined more correctly (with less error). The lines 614.31 nm (mult. no. 1) and 540.00 nm (mult. no. 3) show a considerable disagreement in shift values from the mean value within the corresponding multiplet. The reason for this disagreement is due to the difference of excitation energies in upper energy levels within the same multiplet. For this reason it would be necessary to calculate their shifts separately. Highest disagreement between measured and theoretical values is found for the multiplet no. 6, Ne I 585.25-nm line. The theoretically predicted strong dependence of the shift on temperature is not justified for this line of the sixth multiplet. A good agreement between the present measurements and previously measured[2] values has been found. A weak temperature dependence of shifts of multiplets (1, 1′, 3, 3′, 5′, 6, 6′, and 12) are found, as in the case of Stark HWHM.

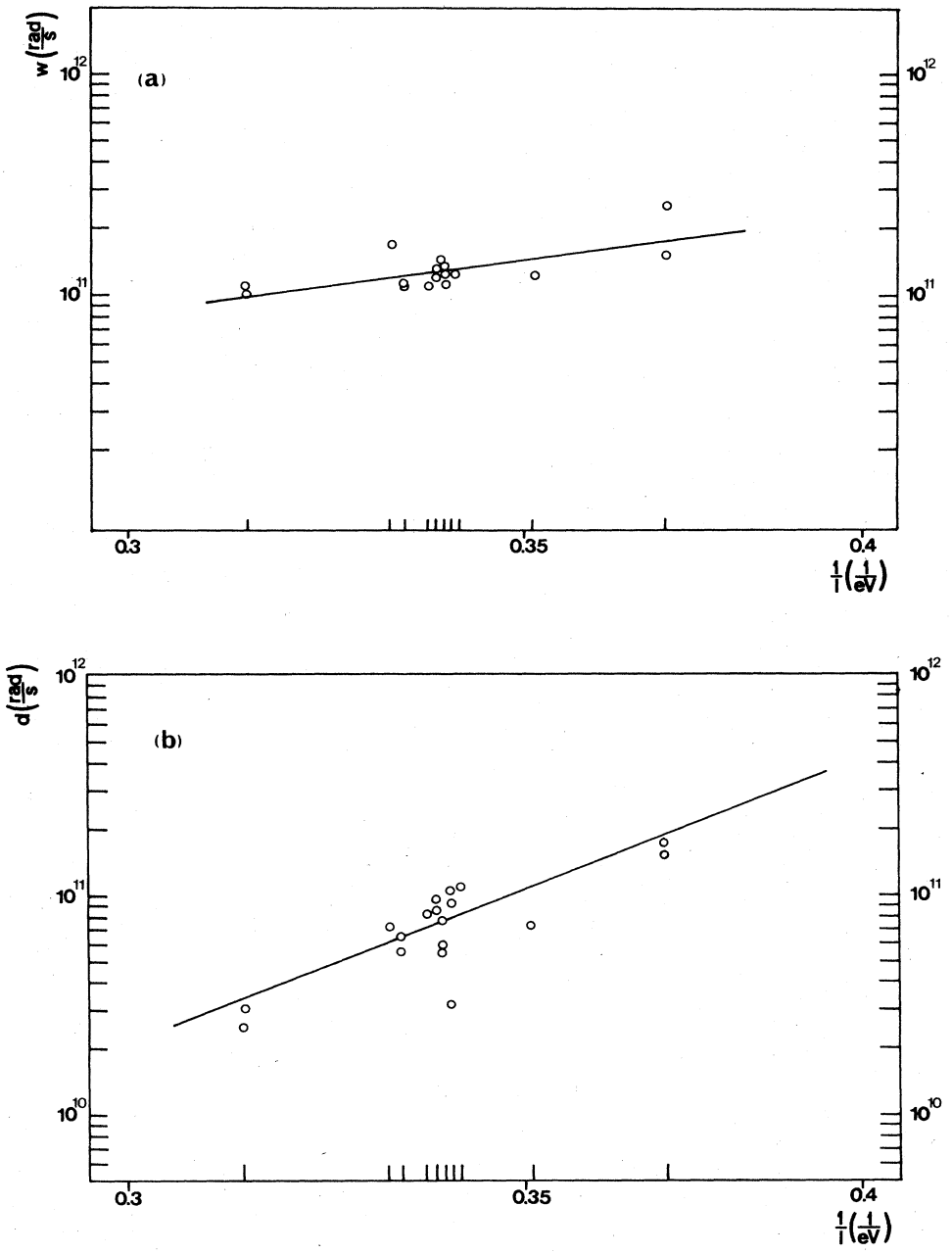

FIG. 3. Stark width (a) and shift (b) vs inverse value of upper-level ionization potential I for $3s$-$3p$ transition array.

IV. STARK WIDTH AND SHIFT DEPENDENCE ON THE UPPER-LEVEL IONIZATION POTENTIAL

Using the Stark width and shift data of the lines originating from the transition array $3s$-$3p$, Figs. 3(a) and 3(b) are constructed. In these figures Stark widths (w) and shifts (d) in angular frequency units are given as functions of the inverse value of the upper-level ionization potential (I) of the corresponding line. From these figures it is evident that in a log-log scale w and d are linear functions of $1/I$ with correlation factors better than 0.70. Namely, w and d can be expressed as

$$w = 2.28 \times 10^{12} I^{-2.69} \text{ rad/s}$$
$$d = 2.46 \times 10^{15} I^{-9.62} \text{ rad/s} \quad (3)$$

if I is given in eV which is in accordance with Eqs. (1) and (2). This can be regarded as very satisfactory since the trend obtained using Griem's[5] theoretical data is in very good agreement with the one obtained using our experimental data and the experimental data of the other authors.[1,2] As far as the difference in Stark broadening and shift parameters within a particular multiplet is concerned it is clear that comparison has to be done in angular frequency units instead of in nm units. If then there is disagreement it can be explained due to a difference in the upper-level energy in the energy spectrum of the corresponding emitter, i.e., using the Stark parameters' dependence on the upper-level ionization potential.

V. CONCLUSION

On the basis of the above considerations it is possible to conclude the following.

(a) Our experimental data for the majority of the investigated lines are in very good agreement both with Griem's theoretical results,[5] and with experimental results of other authors[1,2] taking into account the experimental error of $\pm 15\%$ and the uncertainity of theoretical results of $\pm 10\%$.

(b) The corresponding disagreements, where they exist, can be explained on the basis on the established Stark parameters' dependence on the upper-level ionization potential of the particular line.

(c) The Stark broadening and shift dependence on the upper-level ionization potential is of fundamental importance and can be used as a criterion for the correctness of experimental determinations and theoretical calculations of Stark parameters, and for theoretical predictions of the Stark parameters of a line not investigated so far but originating from the given transition.

ACKNOWLEDGMENTS

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