PHYSICAL REVIEW A VOLUME 29, NUMBER 6 JUNE 1984

Stark-broadening measurements of singly ionized xenon

J. Richou
Université de Toulon, Château Saint Michel, F-83130 La Garde, France

S. Manola
Institute of Physics, P.O. Box 57, 11001 Beograd, Yugoslavia

J. L. Lebrun and A. Lesage
Departement Physique des Etoiles et Galaxies, Observatoire de Paris, F-92195 Meudon Cedex, France

(Received 2 December 1983)

Linewidths of four visible Xe II lines are measured in a conventional shock tube. The Stark effect is the dominant broadening mechanism. Electron densities vary widely over the range $(1-15)\times 10^{16}$ cm^{-3}, but temperatures remain in the narrow range 7800—8400 K. Great care has been taken to minimize possible systematic errors in the electron-density and optical-depth measurements.

I. INTRODUCTION

In a recent paper, Wiese and Konjevic[1] presented a comprehensive set of experimental data in order to demonstrate the strong dependence of Stark widths on atomic structure. Experimental data were used exclusively, since plasma line-broadening calculations contain numerous approximations, and may not show the expected regularities. For the Stark widths of alkaline-earth resonance lines (Be II—Ba II) recent experimental data for Mg II and Ca II (Refs. 2 and 3) are in disagreement with previous ones.[4,5] A comparison with experimental data for the rare gases (mirror image of the alkaline earths) plotted on the same graph[6] does not help to draw a conclusion, since a similar disagreement exists between the values of different authors. The purpose of these Xe II linewidth measurements is to contribute an additional reliable set of data, in order to have a good base to demonstrate the above-mentioned regularities and similarities.

II. EXPERIMENTAL

The light source is a conventional shock tube[7] filled with neon and a small admixture of xenon, and in some experiments argon, or iron carbonyl Fe(CO)$_5$. Xenon partial pressures in the test section were varied by a factor of 1.6 in order to check possible self-absorption. Intensity ratio measurements of Xe II at $\lambda = 5372.4$ Å to that at 5419.1 Å which have almost the same upper level give a standard deviation of 0.04 for $N = 8$ experiments. The driven gas is hydrogen, and breaking pressures varied from 56 to 90 bars. All observations (Fig. 1) are done in the same cross section of the tube and the spectra are recorded in the reflected shock wave. A REOSC HA grating spectrograph,[8] with an inverse linear dispersion of 3 Å mm^{-1} in the focal plane, is used with an optical multichannel analyzer (OMA II) equipped with an intensified silicon photodiode array detector (RETICON), to record the Xe II line profiles. The spectral resolution of the spectrograph is limited by the spatial resolution of the detector (25 μm between two pixels). The overall resolution of the spectrograph-plus-detector system is measured *in situ* by recording thorium spectra emitted by a high-frequency excited source, under the same conditions as the shock-tube spectra. The apparatus function is assumed to be

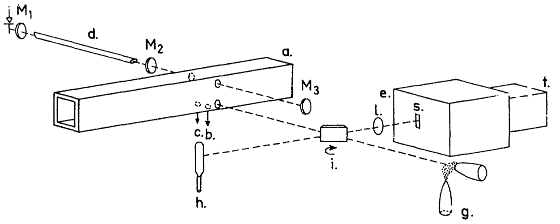

FIG. 1. Shock-tube test section and associated instrumentation: *a*, test section of i.d. 4×4 cm, fitted with quartz windows near the reflecting wall; *b*, quartz pressure transducer; *c*, photodiode; *d*, laser interferometer; *e*, echelle grating spectrograph; *f*, optical multichannel analyzer with intensified silicon photodioide array; *g*, carbon arc; *h*, thorium source; *i*, movable mirror; *l*, lens; and *s*, entrance slit.

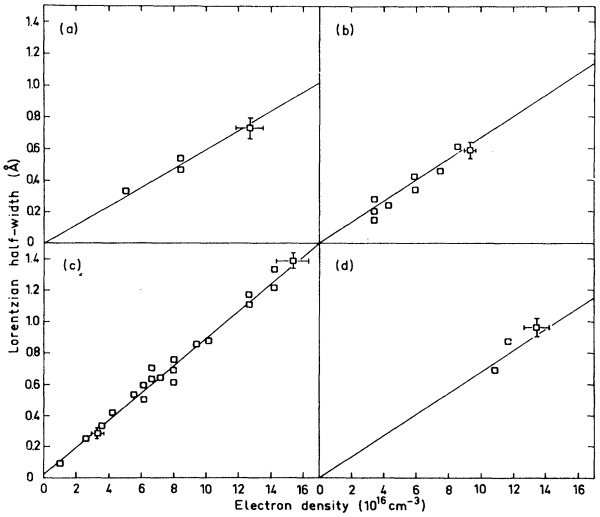

FIG. 2. Linewidths [(a)—(d)] for Xe II $\lambda = 5339$, 5372, 5419, and 5439 Å, respectively, vs electron density.

TABLE I. Iron lines selected for temperature measurements and optical thickness checks of the plasma. Notations and numbers in columns 1—6 are as in Ref. 14. R_c is the calculated line-intensity ratio; $\overline{R}_m$ is the mean for seven experiments of the corresponding measured ratio.

Multiplet	λ (Å)	E_k (cm^{-1})	g_k	A_{ki} (10^8 s^{-1})	Accuracy	R_c	$\overline{R}_m$	Standard deviation	$\frac{\overline{R}_m - R_c}{R_c}$
zG^o-e^3H (1165)	5410.91	54 555	9	0.49	C^+				
a^5F-z^5D^o	5371.49	26 340	5	0.0105	B^+				
(15)	5405.77	26 479	3	0.0109	B^+	1.40	1.30	0.004	7%
	5397.13	25 900	9	0.002 59	B^+				
z^5G^o-e^5H	5383.37	53 353	13	0.59	C^+	1.45	1.70	0.005	20%
	5369.96	58 874	11	0.48	C^+				

Gaussian and the Lorentzian contribution is unfolded from the Voigt profile using the tables of Davies and Vaughan.[9] Observed Xe II line profiles are 1.4 to 15 times larger than the thorium ones. The time of exposure was adjusted from 5 to 50 μs, depending on the physical conditions in the plasma, in order to have the electron density as constant as possible during the time of exposure and an acceptable signal-over-noise ratio.

The electron density N_e is measured with an Ashby-Jephcott interferometer[10] and checked by measuring the $\lambda = 5451$ Å argon linewidth and line shift,[11] recorded simultaneously with the $\lambda = 5419$ and 5439 Å Xe II lines. The 3.39-μm radiation of the He-Ne laser is used as the interferometer source. The ratio $K_e N_e / K_1 N_1$ of the specific refractivity of electrons and neon atoms is -28 at 3.39 μm for $\text{Ne} = 10^{16}$ cm^{-3} and for a pressure variation of 1 bar at 10 000 K; therefore, the neutral contribution to the refractive index can be considered as negligible. Measurement precision is better than 10% for the interferometric measurements and 30% for the electron density determined by the argon line-shape data.[12] The agreement between the values provided by the two methods is (8—20)%, depending on the experiments.

Filling pressures and compositions of the test gas are measured by two capacitive gauges (MKS-Baratron). The pressure in the shock-heated gas is measured with a piezoelectric transducer (Kisler) with a 5% accuracy. Temperatures are calculated using the Saha relation;[13] and in the case when iron was added to the test gas, they are calculated from the intensity ratio of the FeI 5369-Å line to that at 5371 Å and the 5405-Å line to that at 5410 Å, the transition probabilities of which are known with an accuracy better than 15%.[14] In order to check the optical thickness of the plasma, the 5405- and 5397-Å lines (multiplet 15) and the 5483- and 5369-Å FeI lines (multiplet 1146) are measured at various pressures in the same experiment and in different experiments. Table I shows that the intensity ratios of lines within a multiplet are constant when emitter populations vary by a factor of 1.6, and are in agreement with the calculated ones within the mutual error bars. A carbon arc is also used in order to compare lines and blackbody intensities at the same temperature and wavelength. All Xe II and FeI lines of interest were found to have an intensity below 8% of that of the blackbody at 8400 K.[15]

III. RESULTS

The measured full width at half maximum (FWHM) of the Xe II 5339-, 5372-, 5419-, and 5439-Å lines have been measured for 3—21 experiments, depending on the lines. The unfolded linewidths are shown in Fig. 2. They are corrected for Doppler broadening (0.032 Å), while neutral and resonance broadening are negligible. Linear regression for the Xe II 5419-Å line data shows a nonzero intercept, but the 0.018-Å residual width for $N_e = 0$ is well within the experimental error bars which include uncertainties in the electron density, linewidth measurements (including wing relative to background position), and unfolding procedure.

TABLE II. Stark-broadening parameters of Xe II visible lines. FWHM in Å (denoted W) are normalized to $N_e = 10^{17}$ cm^{-3}. Present measurements (W_P) are at $T = 8000$ K; previous measurements W_M (Ref. 16) are at $T = 10\,000$ K; semiempirical calculations W_{se} (Ref. 17) are for $T = 8000$ and 10 000 K.

Transition	λ (Å)	E_k (cm^{-1})	$T = 8000$ K W_P (Å)	$T = 10\,000$ K W_M (Å)	$T = 8000$ K W_{se} (Å)	$T = 10\,000$ K W_{se} (Å)
$6p\ ^4D^o_{3/2}$—$6d\ ^4D_{7/2}$	5339.33	135 507	$0.60 \pm 18\%$[a]			
$6s\ ^4P_{5/2}$—$6p\ ^4P^o_{3/2}$	5339.38	111 792				
$6s\ ^4P_{3/2}$—$6p\ ^4P^o_{1/2}$	5372.39	113 672	$0.67 \pm 15\%$	$0.90 \pm 15\%$	0.87	0.98
$6s\ ^4P_{3/2}$—$6p\ ^4D^o_{5/2}$	5419.15	113 512	$0.90 \pm 10\%$	$1.07 \pm 15\%$	0.89	1.00
$6s\ ^2P_{3/2}$—$6p\ ^2S^o_{1/2}$	5438.96	121 179	$0.67 \pm 22\%$			

[a] Blended lines

The Xe II Stark-broadening parameters at $Ne = 10^{17}$ cm^{-3} and $T = 8000$ K are shown in Table II and compared with previous measurements[16] and semiempirical calculations.[17] Very good agreement is found for the Xe II 5419-Å line with semiempirical calculations and previous measurements. For the Xe II 5372-Å line the agreement with previous measurements is also very good; but the disagreement with semiempirical calculations cannot be explained by the atomic structure. The Xe II 5419- and 5372-Å lines both belong to the same kind of transition. They share the same lower level and have upper levels close together, and there is no perturbing level very close to either of them.[18] For the Xe II 5339- and 5438-Å lines no prior experimental data are published.

IV. CONCLUSION

Present photoelectric measurements confirm previous photographic findings.[16] The fact that the Xe II 5419- and 5372-Å linewidths do not behave as expected might be due to a misclassification. The spectrum of xenon has not been revised since Humphrey's work.[19] Even if present measurements help to clarify the situation regarding the rare-gas Stark linewidth regularities, the authors' opinion is that other reliable measurements are needed, especially for the Kr II 5*s*-5*p* transitions, in order to complete the base of experimental data needed to demonstrate quantitatively the dependence of Stark widths on atomic structure.

---

[1] W. L. Wiese and N. Konjevic, J. Quant. Spectrosc. Radiat. Transfer 28, 185 (1982).

[2] C. Goldbach, G. Nollez, P. Plomdeur, and J. P. Zimmermann, Phys. Rev. A 25, 5 (1982).

[3] C. Goldbach, G. Nollez, P. Plomdeur, and J. P. Zimmermann, Phys. Rev. A 28, 234 (1983).

[4] D. Hadziomerspahic, M. Platisa, N. Konjevic, and M. Popovic, Z. Phys. 262, 169 (1973).

[5] C. Fleurier, S. Sahal-Bréchot, and J. Chapelle, J. Quant. Spectrosc. Radiat. Transfer 17, 595 (1977).

[6] J. Richou, S. Manola, A. Lesage, D. Abadie, and M. H. Miller, in *Proceedings of the Sixteenth International Conference on Phenomena in Ionized Gases, Düsseldorf,* edited by W. Bötticher (Insitute for Theoretical Physics, Düsseldorf, 1983).

[7] A. Lesage, Thèse de Doctorat d'Etat, Université Paris XI, 1977 (unpublished).

[8] A. Bayle, J. Espiard, C. Breton, M. Capet, and L. Herman, Rev. Opt. Theor. Instrum. 4, 585 (1962).

[9] J. T. Davies and J. M. Vaughan, Astron. J. 4, 1302 (1963).

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

[11] P. Ranson and J. Chapelle, J. Quant. Spectrosc. Radiat. Transfer 14, 1 (1974).

[12] N. Konjevic and W. L. Wiese, J. Phys. Chem. Ref. Data 5, 209 (1976).

[13] H. R. Griem, *Plasma Spectroscopy* (McGraw-Hill, New York, 1964).

[14] J. R. Fuhr, G. A. Martin, W. L. Wiese, and S. M. Younger, J. Phys. Chem. Ref. Data 10, 305 (1981).

[15] D. Einfeld and D. Stuck, Z. Naturforsch 33a, 502 (1978).

[16] M. H. Miller, A. Lesage, and D. Abadie, Phys. Rev. A 25, 2064 (1982).

[17] H. R. Griem, Phys. Rev. 165, 258 (1968).

[18] M. S. Dimitrijevic, Astron. Astrophys. 112, 251 (1982).

[19] C. J. Humphreys, J. Res. Nat. Bur. Stand. 22, 19 (1939).