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Experimental stark widths of Xe II and trends in the broadening of homologous rare-gas ions

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Stark broadening of 6s-6p and 5d-6p singly ionized xenon lines is measured as a function of electron density $6 \leq N_e \leq 18 \times 10^{16}$ cm^{-3} in a gas-driven shock tube. Doppler and resonance broadening, and radiative trapping, are negligible at $10.2 \leq T \leq 12.4 \times 10^3$ K and $2 \leq N_{Xe} \leq 8 \times 10^{17}$ cm^{-3}. Results are compared with theoretical predictions and with trends in the broadening of ions in the homologous structure sequences: Ne II, Ar II, Kr II, Xe II and Mg II, Ca II, Sr II, Ba II.

I. INTRODUCTION

Experimental[1,2] Stark-broadening parameters have been recently reported for leading visible transition arrays of Kr I,[3,4] Kr II,[4] and Xe I.[3,5] Measured Stark widths for Xe II, heretofore unavailable, permit an examination of homologous structure's influence on braodening in the sequence Ne II, Ar II, Kr II, and Xe II.

As the body of Stark-broadening data assumes proportions amenable to statistical treatment,[1,2] there has arisen an appreciation of structure-related regularities. These include relationships between multiplets of individual spectra[6,7] and systematic trends within isoelectronic and homologous sequences.[8–12] Regularities in the Stark widths of homologous atoms and ions were initially recognized in resonance lines of alkalis and alkali earths.[8,9,11] More recently, they have been noted in prominent visible lines in cases where central force fields dominate fine-structure splitting.[10,12] The prevalence of these systematic trends is a matter of continuing inquiry.[8–12]

II. EXPERIMENTAL

The gas-driven spectroscopic shock tube, absolute photoelectric photometry (for temperature and optical depth determinations) and relative photographic photometry (for recording Xe II and H_β profiles) are described in detail elsewhere.[13–15]

Prior work[16,17] has shown that the luminous plasmas behind first and multiply reflected shock waves conform to the assumption of local thermodynamic equilibrium[7,18] and are free from repeatable inhomogenieties. Laminar boundary layers are present, but pose no reabsorbtion problems for ionic lines.[16]

Test gases for shock heating consist of $0.5-2.0\%$ at xenon in a neon carrier. Doping with $0.3-0.6$ mol % SiH_4 increases the range of plasma electron densities (via the readily ionized silicon) and provides Balmer profiles for plasma diagnosis. Trial runs establish which gas composition, driver, and driven pressure domains effect workable compromises between the criteria:

(1) good signal-to-noise ratios in subject and diagnostic emission lines (at acceptably small optical depths and slit widths),

(2) spanning a broad electron-density range (while minimizing temperature range),

(3) furnishing steady-state test times of sufficient duration for good spectral densities.

Plasma electron densities, $6 < N_e < 18 \times 10^{16}$ cm^{-3}, are determined in each run by fitting (symmeterized) H_β profiles to theoretical Stark shapes.[19,20] In a typical experiment, 10-point profile fittings yield electron densities with an estimated precision of $\pm 15\%$. As a hedge against bias and to flag occasional runs where diagonal shocks are propagated, these data are compared with electron densities computed from measured temperature and pressures.[16] While these redundant data do agree satisfactorily on average, the H_β-derived electron densities are alone used in computing Stark-broadening parameters. This being because (1) they afford the more precise N_e determinations, and (2) this method largely nulls any undetected bias in relative photometric photometry. That is, the ratio of a Xe II line width-to-electron density operationally amounts to taking the ratio of widths for two synchronously recorded profiles of comparable brightness, i.e., Stark width of Xe II/H_β width).[2/3]

Most plasmas' temperatures are within ± 600 K of 11 200 K, with the experimental extremes being 10 200 – 12 400 K. In view of this limited range, no attempt is made to adjust[7,21] the xenon-broadening parameters to a common temperature. In each shot, photoelectrically recorded absolute intensities of H_β and of line reversal of optically thick H_α are used to obtain plasma temperature. The average of these two determinations (which did not differ significantly on average) is reliable to $\pm 5\%$.[16]

Plasma pressures, read from a pair of quartz transducers, are typically

$$5-7\times 10^6\,\mathrm{dyn\,cm^{-2}}[\,N_{\mathrm{tot}}\simeq 3.3-4.6 \times 10^{19}\mathrm{cm^{-3}}]\ .$$

Under these conditions, Doppler broadening is small and van der Waals is negligible with respect to Stark-effect broadening.[7,21] Because xenon is a dilute plasma constituent, resonance broadening and radiative trapping are also expected to be inconsequential.[7,15,21] To test for radiative trapping,[1,2] Xe II line-peak brightnesses are compared to H_α profiles, whose optical depths τ are found directly via the line-reversal technique.[22,23] Xenon profiles with $\tau > 0.3$ are discarded. Those that are

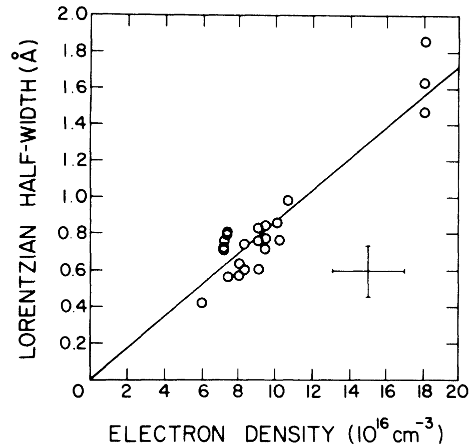

FIG. 1. Stark (slit-corrected Lorentzian component) half-widths of Xe II $6s\,^4P$-$6p\,^4D^o$ lines vs measured electron density at mean-plasma temperature 11 200 K.

retained are converted to their appearance in the optically thin limit by the computer code[24] that translates densitomater scans to intensity versus wavelenght charts (code input includes measured temperature and reversal intensity).

Photoelectric detectors at the focal plane of the photographic spectrograph monitor for temporal variations in emission during the instruments's (50 – 100 μs) sampling time. Spectrograms from nonquiescent plasma exposures are rejected.

To deconvolve instrumental broadening, symmeterized Xe II profiles are fitted at ten points to tabulated[25] Voigt shapes. Instrumental profiles ($\frac{1}{3}$ Å half intensity width and of approximate Gaussian shape), are two- to fourfold narrower than Stark profiles, so that deconvolution can contribute, at most, 10% repeatable error to the results (inclusive of correction for Doppler components).

Random error is attributable mainly to the pro-

TABLE I. Broadening parameters for singly ionized xenon.

Wavelength (Å)	Transition	Experimental[a] range of N_e (10^{16} cm^{-3})	Broadening constant (in Å at 10^{17} cm^{-3})	Error (%) $\sigma\sqrt{n}$	Error (%) Systematic	Semiempirical predictions (Ref. 26) (in Å at 10^{17} cm^{-3})
4603.0	$6s\,^4P_{3/2}$-$6p\,^4D^o_{3/2}$	7 – 18	0.84	3.5	± 15	0.72
4844.3	$6s\,^4P_{5/2}$-$6p\,^4D^o_{7/2}$	7 – 10	0.86	4.2	± 15	0.80
5419.0	$6s\,^4P_{3/2}$-$6p\,^4D^o_{5/2}$	6 – 18	0.95	3.5	± 15	1.00
5292.2	$6s\,^4P_{5/2}$-$6p\,^4D^o_{5/2}$	6 – 18	0.93	5.1	± 15	0.95
5372.4	$6s\,^4P_{3/2}$-$6p\,^4D^o_{1/2}$	7 – 18	0.90	4.3	± 15	0.98
5472.6	$5d\,^4D_{7/2}$-$6p\,^4D^o_{7/2}$	6 – 10	0.96	2.3	± 15	0.87
6051.2	$5d\,^4D_{7/2}$-$6p\,^4P^o_{5/2}$	7 – 10	0.96	2.0	± 15	1.07

[a]Temperature range: 10 200 – 12 400 K.

nounced grain of the fast emulsions (types Kodak 2475 and 103F). Grain noise limited the precision of a typical profile-width determination to about $\pm 10\%$ for the prominent Xe II lines reported here.

III. RESULTS AND DISCUSSION

Measured Xe II Stark half-widths (i.e., full widths at half intensity) are plotted against electron densities in Fig. 1. Data for three $6s\,^4p$-$6p\,^4D^o$ lines (λ4603.0, λ4844.3, and λ5419.0), normalized to a common wavelength[6] of 4700 Å, are aggregated in this display. All deviations from the best-fit (impressed zero intercept) line are within estimated random error.

Stark half-widths at $N_e = 10^{17}$ cm^{-3} for the strong, isolated Xe II lines are presented in Table I. Mean-plasma temperature is 11 200 K. When allowance is made for wavelength dependence, $\Delta\lambda = (\Delta\mu/\mu)\lambda$, all members of multiplets and supermultiplets exhibit (within experimental jitter) equal susceptibility to Stark broadening.[6,21] Theoretical predictions consist of authors' application of semiempirical formulas and Gaunt factors.[26] These are applied to the five levels most strongly perturbing the lines' upper states and the two levels most affecting lower states. In terms of both average value (0.99) and standard deviation (10%), the ratio of semiempirical-to-experimental widths accord with results of tests of this approximation on ions of medium and high atomic weight.[12,27]

Alkali-earth ionic resonance lines measured in a single experiment[11] disclose clear trending of Stark broadening within the homologous sequence Mg II, Ca II, Sr II, and Ba II. The prospect that similar trending might occur in leading transition arrays of rare-gas ions is suggested by the facts that

(1) the two homologous sequences are structural analogs, one set involving a single electron orbiting a closed shell and the other having shells closed except for a one-electron "hole"; and

(2) corresponding members of the two sequences have comparable effective principal quantum numbers.

Multiplet-average experimental width for $ns\,^4P$-$np\,^4D^o$ lines of Ne II,[28] Ar II,[1] and Kr II,[4] adjusted[7,21] to 11 000 K, are compared with present Xe II results in Fig. 2. Error bars represent the larger of spread in intramultiplet widths or estimated experimental error. (Choice of principal quantum number n for the independent variable is discussed shortly.) Similarly normalized broadening parameters for ms-np ionic resonance lines of alkali-earth ions are also plotted in Fig. 2. For these, an expanded ordinate scale is provided to facilitate comparison of $(1/w)(\Delta w/\Delta n)$ for the two homologous sequences. Another set of $3 \le n \le 6$ measured widths[29] is available for this sequence, but is not utilized here as it was obtained at threefold higher temperatures. There is a multiplicity of measurements for Mg II and Ca II resonance lines,[1,30] as well as theoretical predictions spanning the entire sequence Be II – Ba II.[31] For individual lines, discrepancies between these data can be as large as

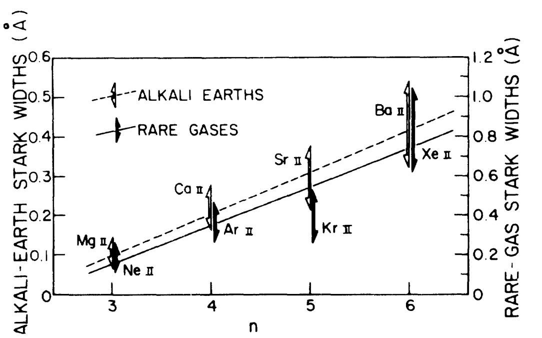

FIG. 2. Experimental Stark half-widths for rare-gas (Refs. 1, 3, 4, and 28) and alkali-earth ion (Ref. 11) homologous sequences vs principal quantum number. Multiplet-averaged data ($ns\,4P$-$np\,^4D^o$ for rare-gas ions and $ns\,^2S$-$np\,^2P^o$ for alkali-earth ions) are adjusted to Ne$=10^{17}$ cm^{-3}, $T \simeq 11\,000$ K.

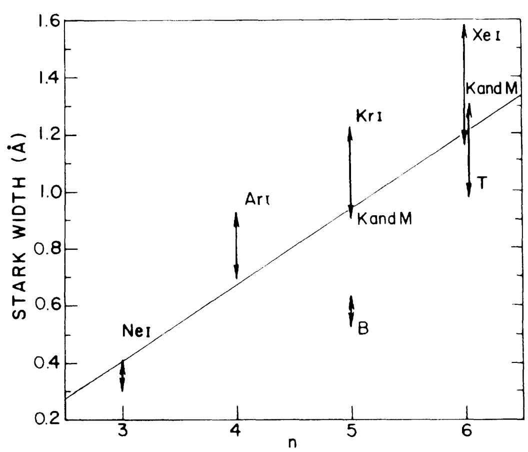

FIG. 3. Array averge (ns-np') Stark widths for neutral rare gases (Refs. 2–5) plotted as implicit function of principal quantum number. Data for Ne I and Ar I are from critical compilations (Ref. 2). For Kr I, results of Klein and Meiners (Ref. 3) and Brandt *et al.* (Ref. 4) are denoted by *K*, *M*, and *B*, respectively. Xenon widths measured by Klein and Meiners and by Truong-Bach *et al.* (Ref. 5) are denoted *K*, *M* and *T*, respectively.

a factor of 2. However, the logarithmic slopes $(1/w)(\Delta w/\Delta n)$ from all treatments agree with the depicted one[11] to within the error shown in Fig. 2. Regression-line slopes for the two sequences are similar despite the depression in the rare-gas ion fit caused by Kr II.

Stark widths for some Kr I lines were measured together with the Kr II data in question.[4] Systematic trends have assisted in assessing experimental atomic data elsewhere,[1,32,33] leading us to seek implications from *ns-np'* line broadening in the sequence Ne I,[2] Ar I,[2,3] Kr I,[3,4] and Ke I,[3,5] whose transition array-averaged broadening parameters (at 10^{17} cm^{-3}) are shown in Fig. 3. Klein and Meiners have identified a proness for their measurements to yield too large widths.[3] As was the pattern for ionic lines, the neutral line broadening reported by Brandt *et al.*[4] is seen to fall markedly below the neutral set's regression line. Adjusting Brandt's Kr I data by a factor of ≈ 1.5 would bring it onto the neutrals' trend line. The same scaling would also raise Kr II onto the rare-gas ionic trend line and would make the latter's slope more closely approach the slope for the alkaline-earth ions line (Fig. 2).

Most[9,12,33,34] homologous sequence-broadening trends have been expressed as implicit functions of inverse powers of ionization potential χ. The decline of ionization potential as one descends a column of the periodic table does heuristically prompt expectations that

(1) wavelengths will increase as systems become heavier. Accordingly, perturbations of equal strength will induce greater broadening the further one progresses in a homologous sequence;[7]

(2) due to the f sum rule,[35] dipole perturbing transitions tend on average, to increase;

(3) energy separation from perturbing levels also trends to progressively decline.

Plausibility of these expectations stems from use of a scaled hydrogenic description for emitting states. However, for $n^* < 2$ (corresponding to lower levels of cases here investigated), the Coulomb approximation is of dubious reliability.[30] For the rare-gas ions it is found that Stark widths correlate slightly better (0.90) with n than (0.88) with χ^{-1}. Recognizing that n and χ^{-1} are theoretically expected to be covariants (and for this set, the correlation is significant to 99%), broadening trends are here presented in terms of n, the simpler, integral variable.

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