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Dependence of the Stark broadening on the emitter charge for the $3s$-$3p$ transitions of Li-like ions

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The Stark widths of the $3s$-$3p$ transitions for the Li-like ions C IV, N V, and O VI were measured for the plasma parameters $n_e = 1.8 \times 10^{24}$ m^{-3} and $kT_e = 12.5$ eV. Within the error limits, the measurements clearly show a Z^{-1} dependence of the Stark width on the emitter ionization stage Z ($Z = 4$ for C IV), whereas calculations within the electron-impact approximation yield Stark widths more nearly proportional to Z^{-2}.

INTRODUCTION

The Stark broadening of spectral lines from nonhydrogenic ions of low ionization stage Z (up to $Z = 3$) is rather well known, but only a few measurements have been made of Stark widths for higher Z values.[1-3] Reliable measurements of Stark-width scaling with Z would provide a useful test of the different (electron-impact) Stark-width calculations for nonhydrogenic ions at higher Z values, as well as enabling measured Stark widths to be extrapolated to higher emitter charges along an isoelectronic sequence. Measurements of such scaling are presented here. This type of scaling is different in principle from the forms proposed by Purić and co-workers,[2-4] and also leads to a very different conclusion. The $3s\,^2S_{1/2}$-$3p\,^2P^0_{3/2}$ transitions of the Li-like ions C IV, N V, and O VI were chosen for our measurements since these lines are isolated and therefore not affected by quasistatic Stark broadening. Our light source was a gas-liner pinch[5] which produced a hydrogen plasma with an electron density of about 1.8×10^{24} m^{-3} and a temperature of about 12.5 eV.

MEASUREMENTS

The gas-liner pinch is essentially a z pinch with a special gas inlet system which gives rise to certain important properties: The gas-liner pinch used in this work produces a hydrogen plasma containing a small amount ($\leq 1\%$) of impurity in the center of the plasma column. The type and (within certain limits) amount of this impurity can be chosen without changing the plasma parameters significantly. The spectral lines of this impurity are only emitted from a region with rather homogeneous plasma parameters, without being affected by a cooler boundary layer (thus avoiding self-absorption effects), and they are usually optically thin. These properties are extensively described in Refs. 5 and 6 and were used mainly for line broadening studies[7-10] in previous experiments.

In this experiment, we used these special properties to measure the Stark broadening of the $3s\,^2S_{1/2}$-$3p\,^2P^0_{3/2}$ transitions of C IV (impurity gas CH_4), N V (N_2), and O VI (CO_2). The line profiles were recorded by an optical multichannel analyzer system (EG&G model OMAII) with a 1-m monochromator (Spex model 1704, 1200 lines/mm grating). The apparatus profile was a Voigt profile with 0.025-nm Gaussian and 0.05-nm Lorentzian full half-width. Since the spectral radiance in the center of the resonance lines $2s$-$2p$ of C IV is less than 1% of the blackbody value, these lines are optically thin (see also Ref. 8), and thus the measured $3s$-$3p$ lines even more so.

The plasma parameters were measured by 90° Thomson scattering. The experimental uncertainties on the measured electron density and temperature values are less than 20%. The experimental setup and the Thomson scattering experiment are described in Ref. 10.

The Stark widths of the $3s\,^2S_{1/2}$-$3p\,^2P^0_{3/2}$ transitions were determined in the following way: A Voigt profile was fitted to the average spectrum over about ten single spectra, measured for the same plasma conditions. Examples of these average spectra are shown in Fig. 1. The Voigt profile includes the apparatus, the Doppler, and a Stark (Lorentzian) profile with a full half-width as fitting parameter. In this way, the Stark widths are determined for two different plasma conditions ($n_e = 2.05 \times 10^{24}$ m^{-3}, $kT_e = 13$ eV and $n_e = 1.8 \times 10^{24}$ m^{-3}, $kT_e = 12.5$ eV) and then normalized to $n_e = 1.8 \times 10^{24}$ m^{-3} and $kT_e = 12.5$ eV by assuming a linear density dependence of the Stark widths and ignoring the small temperature variation.

The mean values of the Stark widths are given in Table I, along with the corresponding experimental uncertainties. These account for the reproducibility of the plasma, the average over the two plasma conditions, and the fitting process, the latter being the main source of uncertainty especially in the case of C IV.

The measured Stark widths (divided by the square of the wavelength) plotted versus the emitter ionization stage Z in Fig. 2 show almost exactly a Z^{-1} dependence. This result is not affected by the uncertainties of the plasma parameter determination, because the measurements were made in succession under the same plasma conditions.

The Doppler widths, which comprise some 4%–8% of the total measured widths, are determined by assuming that the electron and ion temperatures are equal. This assumption is justified by the results of Thomson scattering measurements,[10] which also reveal lack of turbulence in the electron and proton velocity distributions at the time of measurement. (Lack of turbulence in the ion impurity velocity distribution is to be expected, since only electrons

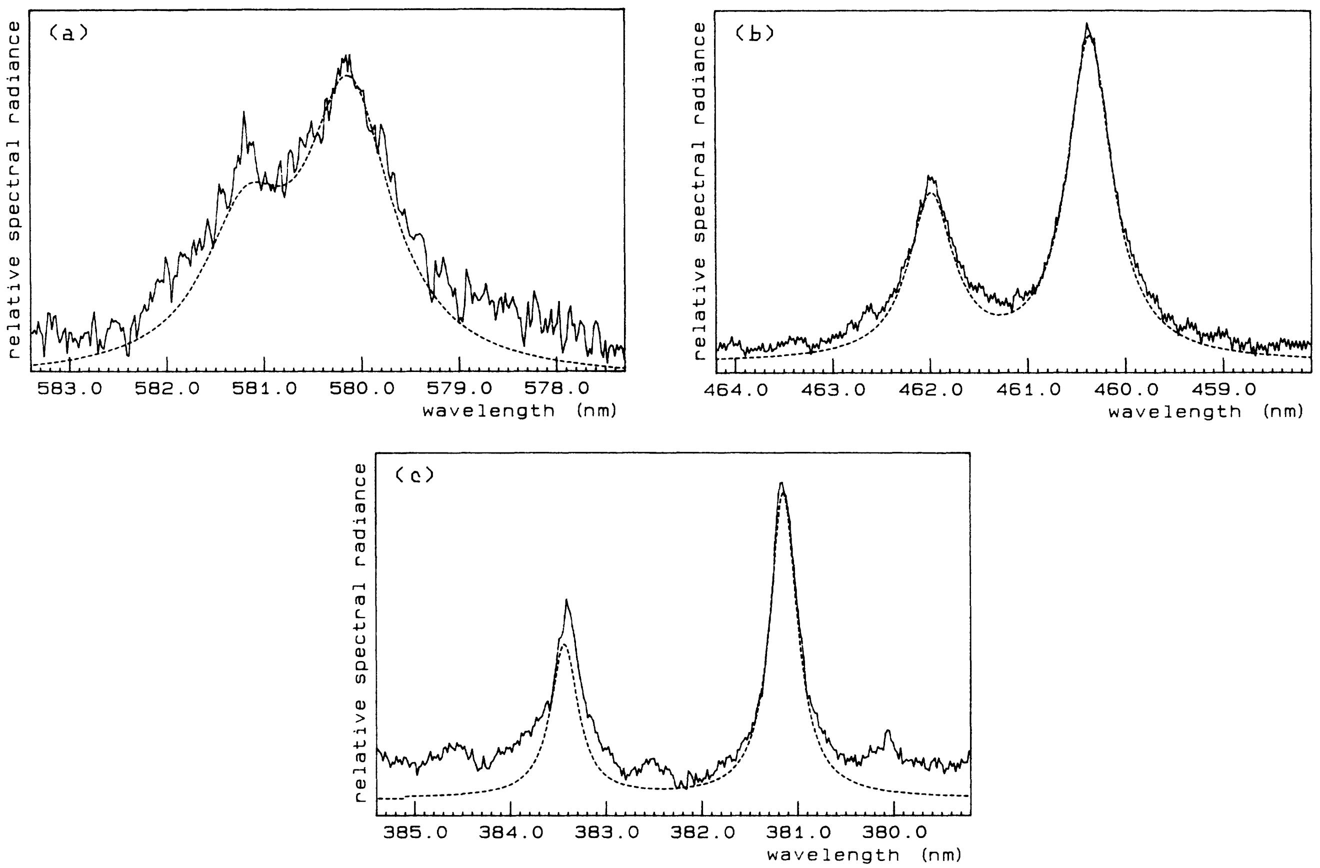

FIG. 1. Measured spectra of the $3s$-$3p$ transition at $n_e = 1.8\times10^{24}$ m^{-3} and $kT_e = 12.5$ eV. A background subtraction was performed. The dashed profile is a summation of two equal Voigt profiles, centered at different wavelengths: The profile at the lower wavelength was fitted to the $3s\,^2S_{1/2}$-$3p\,^2P^o_{3/2}$ transition (see text) and the intensity of the profile at the greater wavelength was weighted by a factor of 0.5. (a) C IV; (b) N V; (c) O VI.

and protons are driven inward in the initial implosion phase of the gas-liner pinch.[5]) The impurity temperature is in turn equal to that of the electrons and protons, since the proton-other-ion equilibration time[11] (e.g., 3 ns for O VI ions) is much less than the implosion time (about 50 ns). This conclusion is confirmed by measurements[8] of the optically thin resonance transitions $2s$-$2p$ in C IV, whose profiles are essentially entirely instrumentally broadened. Assuming the noninstrumental broadening in this case to be entirely due to ion motion, we would obtain a temperature of order 10 eV, i.e., in satisfactory agreement with the value stated above. The effect of magnetic fields on our spectra is believed to be insignificant. Zeeman broadening[12] would only exceed the already unimportant Doppler broadening for magnetic fields well in excess of those obtainable from pressure balance beyond maximum compression.

COMPARISON WITH THEORY

The measurements have been compared in Table I with calculations based upon four theoretical approaches in the literature,[12-16] and the empirical scaling relations of Pur-

TABLE I. Experimental and calculated (electron impact) Stark width of the transition $3s\,^2S_{1/2}$-$3p\,^2P^o_{3/2}$ for $n_e = 1.8\times10^{24}$ m^{-3} and $kT_e = 12.5$ eV. All data correspond to the full width at half maximum (FWHM).

		$\Delta\lambda_{\mathrm{FWHM}}$ (nm)						
	Wavelength	Experimental			Calculated Stark width			
Ion	(nm)	Stark width	G[a]	DK[b]	HB1[c]	HB2[d]	B[e]	P[f]
C IV	580.13	1.00 ±20%	0.798	0.601	0.545	0.609	1.080	
N V	460.37	0.492 ±10%	0.303	0.241	0.212	0.251	0.439	0.199
O VI	381.13	0.278 ±10%	0.136	0.113	0.101	0.128	0.216	0.224

[a] Reference 12.
[b] Reference 13.
[c] Reference 14.
[d] Reference 15.
[e] Reference 16.
[f] References 2 and 3.

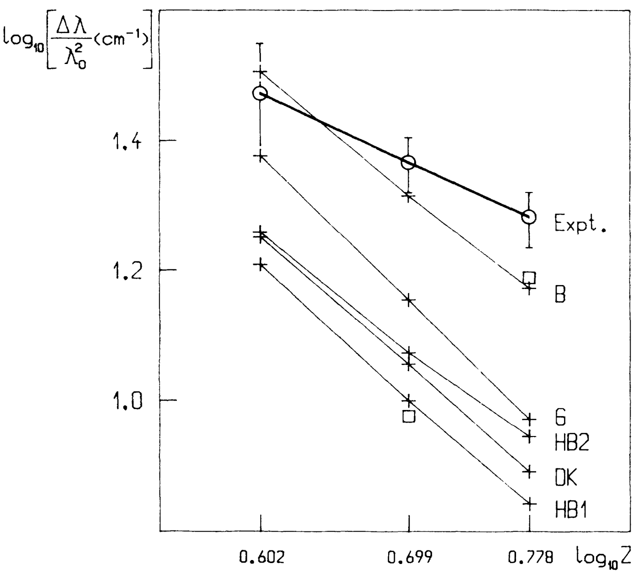

FIG. 2. Experimental (Expt.) and calculated [G (Ref. 12); DK (Ref. 13); HB1 (Ref. 14); HB2 (Ref. 15); B (Ref. 16); □ (Refs. 2 and 3)] electron impact Stark widths of the transition $3s\,^2S_{1/2}$-$3p\,^2P^{\circ}_{3/2}$ for $n_e = 1.8\times10^{24}$ m^{-3} and $kT_e = 12.5$ eV divided by the square of the wavelength and plotted vs the emitter ionization stage Z. The $\Delta\lambda$ and λ_0 values are taken from Table I. The slopes range from -1.78 to -2.29 for the calculated curves, while the experimental slope is $-1.08\pm10\%$.

ić and co-workers (P).[2,3] The results are plotted in Fig. 2. The first two methods[12,13] are based upon the use of semiempirical effective Gaunt factors ($\bar{g}$) in the optically allowed collision-induced transitions which contribute to the linewidth. In the third method,[14,15] semiclassical effective Gaunt factors are calculated self-consistently within the impact and classical-path approximations, and no semiempirical data are employed. Strong collision terms similar to those of Griem (G)[12] have been added to the upper-state contribution only [Hey and Breger (HB1)],[14] as well as to both the upper- and lower-state contributions to the linewidth [Hey and Breger (HB2)],[15] and the upper-lower state interference term has been set equal to zero. The elastic contributions to the broadening have been accounted for by extrapolation of the inelastic terms below threshold with constant $\bar{g}$.

The above discussion applies to impact broadening by free electrons only. The contribution to the broadening from quasistatic or dynamic proton-radiator interactions is estimated[12] to be negligibly small.

The formula of Griem (Eq. 526, Ref. 12) as applied here may be regarded as an overestimate through the omission of the relevant Bates-Damgaard factors. It, therefore, yields linewidths in excess of those calculated from the formulas of Dimitrijević and Konjević (DK),[13] and Hey and Breger.[14,15] The latter formulas are found to yield closely similar values for these linewidths, when strong collision contributions are added for both the upper and lower states of the line. The argument previously employed for the omission of the lower-state strong collision contributions[14,15] presumably no longer applies for larger Z, where the "strong" contribution to the upper-lower state interference term should be relatively small.[12] With the use of method HB2 instead of HB1, the strong collision contribution to the linewidth is increased from 13% to 22% ($Z=4$), 21% to 33% ($Z=5$), and 29% to 44% ($Z=6$). Since the expressions employed for the strong collision terms[12,14,15] are rather approximate, this indicates a need for further refinement of the theory. All three approaches, however, yield significantly smaller widths than the measured values, and moreover scale more nearly as Z^{-2}, rather than as the experimental scaling of Z^{-1}, which is clearly indicated in Fig. 2.

While the scaling relation of Purić *et al.*[3] yields satisfactory agreement with our measurement for O VI, the corresponding prediction[2] for the N V line is very poor. Their formulas[2-4] therefore support neither the experimental nor the theoretical scaling with Z as here obtained.

Lastly, we have repeated the calculations on the basis of the Baranger (B) (1962) theory for nonhydrogenic ions,[16] in which classical Coulomb excitation functions[17] are employed in the electric dipole-allowed contributions to the linewidth. The effective Gaunt factor $\bar{g}$ is thereby replaced by the classical Kramers-Gaunt factor g, which is significantly larger. Elastic contributions to the broadening are again included by extrapolation of the threshold value of g as a constant. For the validity of this theory,[16] it is necessary that the "Coulomb cutoff" to the impact parameter should exceed the cutoff imposed to avoid violation of the unitarity condition.[12] This yields a criterion for the electron temperature in terms of ionization stage Z and principal quantum number, which appears to be satisfied for our conditions, especially for larger Z. Consistent with this approach, therefore, the strong collision contribution to the upper- and lower-state broadening has been omitted, except for a term allowing for higher multipole interactions from Ref. 14. It would probably be better to calculate the quadrupole[17] contributions explicitly, as the strong collision contribution is estimated here to be in the range 10%-20% for the lines under consideration. The relative importance of these higher-order contributions is also indicated by the difference between the methods HB1 and HB2. While the Baranger (1962) theory[16] is seen to yield reasonably satisfactory agreement with the experimental results, without further elaboration, it nevertheless does not provide a simple explanation for the observed scaling of Stark width with Z. This might arise through a complicated interplay of the various contributions included in a refined calculation. Whereas impact broadening calculations[18,19] of the Stark width for hydrogenic ion lines still tend to favor a Z^{-2} scaling, a rigorous calculation of the strong collision terms for nonhydrogenic ions of higher Z still remains to be done. Extension of both measurements and calculations to $3s$-$3p$ transitions from higher-Z ions would therefore be of great interest.

CONCLUSIONS

Measurements of the Stark broadening for the $3s$-$3p$ transitions along the isoelectronic sequence of Li-like ions, from $Z=4$ to $Z=6$, yield an accurate (within 10%) scaling of Stark width with ionization stage as Z^{-1}. This finding is contrary to expectation based upon theoretical models developed to date, in which the dominant (monopole-dipole) contributions to the electron impact broadening scale as Z^{-2}, to a good approximation. A complete explanation of these observations would probably necessitate more precise evaluation of the strong (disruptive, penetrating monopole, and higher-multipole) contributions to the broadening, whose relative importance increases with Z.

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