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Measurements of Stark broadening of some long-wavelength transitions in C V, C VI, and N V

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Profiles of $n=7$ to $n=6$ transitions of C VI, C V, and N V and of the $\Delta n=0$, $n=2$ triplet lines of C V have been measured in a plasma, which was diagnosed by Thomson scattering.

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Profiles of transitions between adjacent levels of high principal quantum number n in multiply ionized atoms are of great interest, since their wavelength can be in the near-ultraviolet or visible spectral region, which is convenient for their observation. Most of the broadening of these lines is due to ion-produced fields, and at high plasma densities they are thus extremely useful for density diagnostics.

Iglesias and Griem [1], therefore, studied the C VI $n=7$ to 6 transition at 3434 Å in a laser-produced carbon plasma. They measured the electron density by shearing plate interferometry and compared the Stark broadening with theoretical calculations by Kepple and Griem [2]. These studies were supplemented by similar measurements of respective lines in B V and N V [3]. In their analysis the authors correct for the variation of the density and hence the line profile along the line of sight.

We now report such measurements of the line profiles of $n=7$ to 6 transitions in C V, C VI, and N V carried out in our gas-liner pinch. Measurements of the C V $n=2$, $\Delta n=0$ triplet transitions were added, since in laser-produced plasmas these lines displayed anomalously large widths, which were attributed mostly to Doppler broadening by hydrodynamic turbulence [4].

The gas-liner pinch has been described previously [5,6]; for spectroscopic studies it offers some unique advantages. It resembles a large-aspect-ratio gas-puff Z pinch, where the so-called driver gas (in our case hydrogen) is injected through a fast-acting valve with an annular nozzle, forming initially a hollow gas cylinder near the wall. This gas is preionized, and after compression a dense plasma column results, 1–2 cm in diameter and 5 cm long. The essential feature is a second fast valve system; it allows one to inject the atomic species of interest (called test gas) along the axis. The amount of test gas can be varied, which readily reveals any optical depth effects on the investigated lines. Furthermore, if the injection is properly timed, the test gas ions remain sufficiently well concentrated in the central part of the plasma column, where the plasma is rather homogeneous [7]. A cold boundary layer thus is practically absent for the emitting ions.

Electron density, temperature, and impurity density were measured on the axis of the plasma column by Thomson scattering [8]. A ruby laser (energy 2 J, pulse length 30 ns) was focused into the plasma, and the scattered light was observed at 90°. It was collected by an $f/10$ optical system. The spectrum was recorded with a one-meter monochromator (SPEX model 1704) fitted with an optical multichannel analyzer in the exit plane. The dispersion was 0.2 Å per channel if a 1200 lines/mm grating blazed for 5000 Å was employed, but with a grating blazed at 10 000 Å measurements in second order were also performed. The system resolution was about three channels in first order. The complete system was calibrated absolutely with the help of Rayleigh scattering in propane. Stray light was undetectable. In order to check the reproducibility of the discharge, the continuum radiation at 5200 Å was monitored with $\frac{1}{4}$-m monochromator equipped with an RCA 1P28 photomultiplier.

Examples of scattered light spectra with argon and xenon as test gas are shown in Ref. [8]. A narrow peak attributed to the test gas ions is superimposed to the normal profile due to scattering from the hydrogen plasma. The scattered light spectra were analyzed using the theory of Evans [9]. Theoretical profiles were convolved with the instrumental function and fitted to experimental profiles employing a "least-squares-fit" procedure, which took into account also the intensity calibration through Rayleigh scattering. The intensity of the "impurity peak" is proportional to the density of the impurity and to the square of its mean charge. This was taken from the equilibrium data of Ref. [10], and thus the density of the test gas ions was obtained, too.

The spectroscopic studies of the emission lines were carried out with the same detection arrangement, of course, with a proper choice of the grating and optical filters. In both cases, the relative sensitivity of all channels was readily obtained *in situ* from discharges without laser and without test gas. This procedure also revealed whether any unwanted impurity lines were present which could influence the measured spectra. Thomson scattering and spectroscopic measurements were performed as function of time after maximum compression; thus, results for different plasma conditions were obtained.

For the measurements of the carbon line profiles, methane was used as test gas. Its pressure in the plenum of the fast valve was selected such that the density of carbon atoms was about 8% for the recording of the C VI line at 3434 Å, which was relatively weak. The wavelength of this line was convenient insofar as the line in second order was close to the wavelength of the ruby laser in first order: this experimental coincidence permitted one to record simultaneously both the C VI line and the scattered light spectrum. Figure 1 shows an example of one recording: the C VI line profile is to the left; the

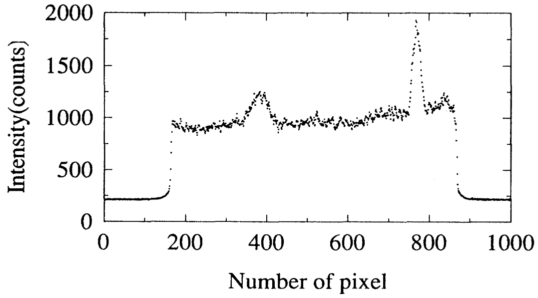

FIG. 1. Experimental spectrum showing profile of C VI line at 3434 Å in second order (to the left) and profile of scattered laser light (to the right).

feature to the right is the scattered light. The discharge parameters were such that the electron density varied from 0.2×10^{18} cm^{-3} to 1.7×10^{18} cm^{-3} and the temperature from 25 eV to 55 eV.

The profiles of the C VI line could be fitted rather well by Lorentzian functions. Estimates confirmed that Doppler broadening could indeed be neglected. Figure 2 shows the widths $\Delta\lambda_{1/2}$ full width at half maximum (FWHM) thus derived versus the electron density n_e from Thomson scattering. Since Kepple and Griem [2] predicted a relation

$$\Delta\lambda_{1/2}=k\times10^{-12}(n_e)^{2/3}\ , \qquad (1)$$

where $\Delta\lambda_{1/2}$ is in Å and n_e is in cm^{-3}, this relation was fitted to the experimental points. The full line represents the best fit, and we obtain

$$k=(8.6\pm1)\ \text{Å}\,\text{cm}^2\ .$$

The constant k depends weakly on the composition of the plasma. For a CH_2 plasma that consists of mostly H^+ and C^{4+}, $k=8.0$ [2], and for pure C^{4+}, $k=8.25$ [3]. For our case, where the carbon density is 8% of the electron density, scaling the result of Ref. [2] gives $k=7.7$. Since the theoretical uncertainty is quoted to be about 20%, the agreement between experiment and theory is good.

The $n=7$ to 6 transitions in C V and in N V, both at 4945 Å, were strong in our plasma, and a test atom density of 0.5% of the electron density was sufficient for their observation. Spectroscopic measurements and Thomson scattering now had to be done during subsequent discharges. Discharges without test gas confirmed the identification.

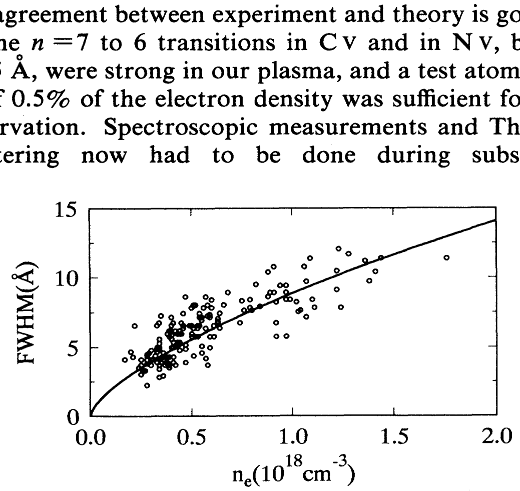

FIG. 2. Measured full width (FWHM) of the C VI line at 3434 Å as function of the electron density from Thomson scattering.

Figure 3 shows examples of profiles of the transition in N V. They were recorded at successive times during the discharge, which correspond to decreasing density. At the time $t=0$ the continuum emission peaks. The continuum underneath the lines is not subtracted; it confirms the density behavior. The evaluation of both lines was identical to that of the C VI transition. The half-width should scale with $n_e^{2/3}$, and Fig. 4 shows $n_e^{2/3}$ from Thomson scattering as a function of time during the discharge as well as the corresponding half-width of the N V line with the scale factor properly chosen. The development of both with time is well correlated and they can be related with each other by a single factor k. It is given for both lines in Table I. Both factors agree well with each other, which is expected theoretically. The temperature of the plasma was typically between 20 and 45 eV.

The density of the test ions was so low that it could be neglected in comparison to the density of the protons; this implies that broadening calculations can be carried out in a pure environment of protons and electrons. Scaling of the factor k for N V as given in Ref. [3] to broadening by protons yields a value of $k=17$, which is lower than the experimental value. However, that scaling of the original calculation for the transition in hydrogenlike C VI to other ions [3] and now to other perturbers is only approximate and more specific calculations for these conditions have to be performed. This is also suggested by the atomic energy levels of C V and N V [11] for $n=6$ and 7, which show sufficient differences that some transitions

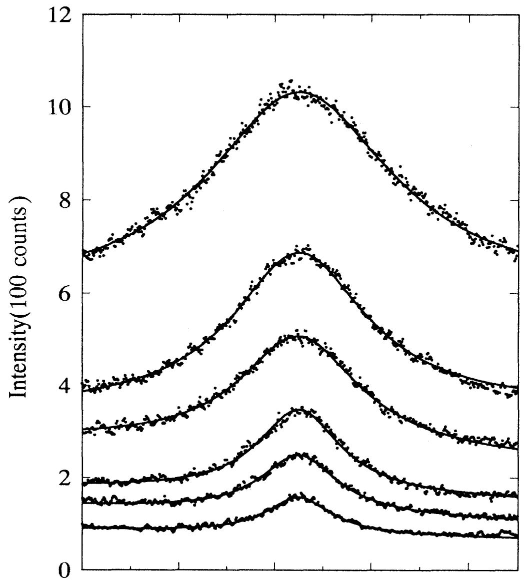

FIG. 3. Spectral profiles of the N V transition at 4945 Å in first order: dots are measured, full lines are best-fit Lorentzian profiles. The underlying continuum has not been subtracted. From top to bottom: $\Delta\lambda_{1/2}$=49.7, 34.2, 30.5, 20.8, 19.5, and 16.3 Å at $t=-30$, 100, 120, 205, 305, and 355 ns.

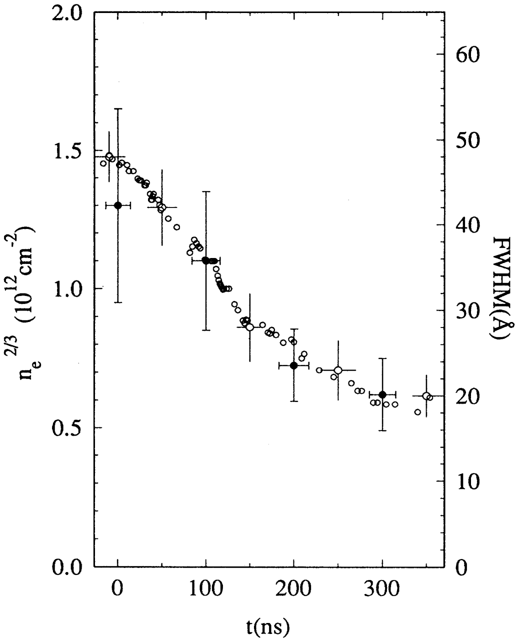

FIG. 4. $n_e^{2/3}$ from Thomson scattering (full dots) and half-width of the N V line (open circles) as a function of time during a discharge.

between different angular momentum states differ in wavelength, resulting in a larger linewidth. Indications of the $7f$ to $6d$ component, whose intensity is estimated to be about 10%, could be seen, for example, at lower electron densities on the line profiles of both C V and N V about 10 Å below the main line. Our experimental value of k should not be used, therefore, at densities much lower than 5×10^{17} cm^{-3}.

Our value of k is also larger than the results from measurements of N V on laser-produced plasmas, where the density was determined interferometrically [3]. At present, this discrepancy is not resolved. However, one should keep in mind that these measurements on a laser-produced plasma were done at several distances from the target, where the plasma was rapidly expanding and recombining; this can lead to a distribution of the population density over different l states which differs from equilibrium and hence results in a different average Stark profile.

We finally studied also the $n=2$, $\Delta n=0$ triplet lines of C V at 2270.91, 2277.25, and 2279.95 Å in fourth order with very good resolution ($\Delta\lambda=0.046$ Å). The lines are broadened essentially by inelastic and superelastic electron collisions yielding a Stark width of [12]

$$\Delta\lambda_{1/2}=3.66\times10^{-13}Xn_e\ , \tag{2}$$

where again $\Delta\lambda_{1/2}$ is in Å, n_e in cm^{-3}, and X is the excitation rate coefficient for the transition $1s2s\ ^3S\rightarrow 1s2p\ ^3P$ in cm^3 s^{-1}. X may be taken from the data compilation of Phaneuf, Janev, and Pindzola [13], which recommend the present "best" values for use. For the temperature range from 20 to 200 eV we approximate the rate coefficient to within 4% by a $(kT_e)^{-1/4}$ dependence and obtain

$$\Delta\lambda_{1/2}=5.9\times10^{-20}(kT_e)^{-1/4}n_e\ . \tag{3}$$

At 100 eV it agrees with the value of Ref. [12]. At higher temperatures additional broadening by ion (here proton) collisions has to be included, but estimates according to Ref. [14] indicate that for our temperatures below 50 eV this can be neglected.

TABLE I. k values for observed transitions $n=7\rightarrow6$.

Ion	λ (Å)	k_{Expt} (Å cm^2)	k_{Theor} (Å cm^2)
C VI	3434	8.6±1	7.7
C V	4945	31±6	17
N V	4945	31±6	17

The Stark width has to be compared with the thermal Doppler width

$$\Delta\lambda_D=7.7\times10^{-5}\lambda(kT_i/A_r)^{1/2}\ , \tag{4}$$

where A_r is the relative atomic mass and kT_i is the ion temperature. For the C V triplet lines and $kT_e=kT_i=kT$ we thus have

$$\frac{\Delta\lambda_{1/2}}{\Delta\lambda_D}\simeq1.2\times10^{-18}(kT)^{-3/4}n_e\ . \tag{5}$$

This indicates that at $kT\approx50$ eV we need about $n_e\approx1.6\times10^{19}$ cm^{-3} for the Stark width to become equal to the Doppler width.

Nevertheless, we carried out measurements at densities lower than that. One reason was the observation that the lines became easily optically thick at high densities. This was evident from their intensity ratio. Therefore, a special discharge condition had to be found for which this was not the case. The density varied from 1×10^{17} to 5×10^{17} cm^{-3} and the temperature from 30 to 90 eV. Figure 5 shows two examples of recorded spectra: (a) is a high-resolution spectrum in fourth order, where the

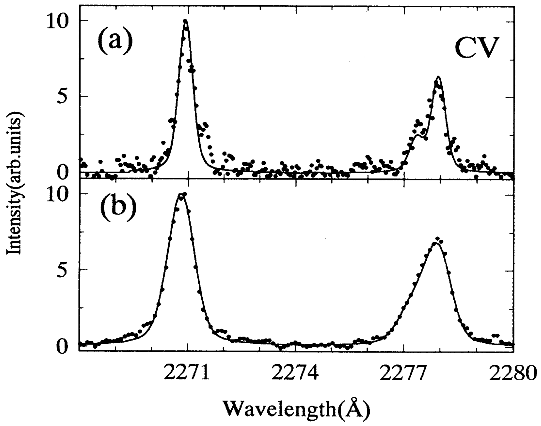

FIG. 5. Profiles of the $\Delta n=0$ triplet lines of C V: (a) spectrum in fourth order, $\Delta\lambda_D=0.35$ Å, $\Delta\lambda_{1/2}=0.01$ Å; (b) spectrum in second order, $\Delta\lambda_D=0.32$ Å, $\Delta\lambda_{1/2}=0.01$ Å.

$J=1\text{-}1$ and the $J=0\text{-}1$ lines are resolved, and (b) has been recorded in second order. The solid lines are convolutions of the apparatus profile, a Doppler profile having a width according to Eq. (4), and a Lorentz profile with a width given by Eq. (3). The density was 5×10^{17} cm^{-3} in both cases, the temperature 50 and 40 eV, respectively. The intensity ratio of the lines was 4.8:1:3 and 4.7:1:3, which is close to the theoretical ratio 5:1:3.

The fit of the theoretical profiles to the experimental ones is reasonably good. This supports the conclusions of Ref. [4], that anomalous widths observed in laser-produced plasmas are not due to anomalous Stark broadening but should be attributed to Doppler broadening caused by hydrodynamic turbulence and differential plasma flow.

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