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STARK BROADENING OF TWO IONIZED-HELIUM LINES BY COLLECTIVE ELECTRIC FIELDS IN A LABORATORY PLASMA*

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Profiles of the He II 4686- and 3203-Å lines observed during the passage of the imploding current sheath in a high-velocity, low-density θ pinch show a broadening that at early times is not due to the usual mechanisms (Doppler, Holtsmark, or Zeeman effects). Most of this broadening is therefore interpreted as due to Stark effects caused by suprathermal collective field fluctuations, and at later times as due to a combination of these and Doppler effects.

Hydrogen lines and ionized-helium lines, which because of their linear Stark effects are very sensitive to electric fields, have served in numerous experiments and analyses of stellar atmospheres as noninterfering and remote probes for electron (or ion) density determinations. The original theoretical basis of this method was provided by Holtsmark,[1] who realized that N singly charged ions per unit volume would produce "microfields" with typical field strengths not much larger than $F_0 \approx 2.6eN^{2/3}$. He calculated the distribution of these fields, assuming ions to be statistically independent. These distributions behave for large F as $1.5F_0^{3/2}/F^{5/2}$, corresponding to $\sim(\Delta\lambda)^{-5/2}$ wings for lines broadened by linear Stark effects. Holtsmark's theory was later improved by allowing for equilibrium correlations between ions[2] and by inclusion of electron effects.[3] The calculated[3] half-width even of the 3203-Å line (which is most sensitive to Stark effects) from particle-produced fields is near or below 0.1 Å for the electron densities encountered in our experiment ($N \lesssim 7\times10^{13}$ cm^{-3}). Estimated Zeeman effects for the magnetic fields involved ($\lesssim$3 kG) are still smaller, and for ion temperatures $kT_i \gtrsim 2$ eV, Doppler broadening would thus appear to be the dominant broadening mechanism, with the ratio of the half-widths given by the ratio of the wavelengths of the lines.

An implicit assumption in the calculations[3] of Stark broadening had been that particles beyond a Debye radius from the radiators would contribute only very little to the broadening. The fields from these particles correspond to the various plasma waves, whose contributions to the total field are indeed negligible when the plasma parameter is small and when equiparton at the particle temperature extends to the relevant collective modes. In contrast, we report experimental evidence for Stark broadening by collective fields greatly in excess of equipartition values, both to warn against the indiscriminate use of the Holtsmark method and to demonstrate an application of this effect to the investigation of plasma turbulence.

The line profiles were measured end-on when the magnetic structure generated by a fast-rising current in the θ-pinch[4] coil passed through the line of sight (at a radius $r = 12.5$ cm with $\Delta r \approx 3$ cm) into a preheated ($N \approx 10^{13}$ cm^{-3}, $T_i \approx T_e \approx 1$ eV) helium plasma containing a ~0.3-kG magnetic field antiparallel to the driving field. Current densities in the magnetic transition layer as measured with probe coils correspond to electron drift velocities reaching $\sim 2\times10^8$ cm/sec or energies of ~10 eV, suggesting very rapid electron heating via the Buneman process[5] to similar temperatures and therefore strong electron-impact excitation of the helium ions. While the underlying electrostatic instabilities are thus more likely than not self-limiting by the time the lines are seen, conditions for ion-sound instabilities remain favorable. The latter can be estimated theoretically[6] to generate fields with energy densities near one-fourth of the electron thermal energy density, or field strengths near 30 kV/cm (compared with mean Holtsmark fields of $\langle F\rangle \approx 8eN^{2/3} \approx 2$ kV/cm), always assuming $N \approx 7\times10^{13}$ cm^{-3} in this example.

Measured profiles as obtained on a shot-to-shot basis and averaged over two or three discharges for each wavelength step are shown on Figs. 1 and 2 at the particular instant (260 nsec from the initiation of the driving current) when the radial gradient of the magnetic "piston" field has its maximum. (Prior to that, photomultiplier signals are too weak.) For the strong line at 4686 Å we measured profiles in both the first (50-μ slits) and second (25-μ slits) order of a $\frac{3}{4}$-m Ebert-Fastie–type monochromator, which then has near-Gaussian apparatus functions of (full) half-widths 0.70 and 0.20 Å, respectively. Since also the measured profiles are almost Gaussian over the range of the apparatus functions, the apparatus correction is easily performed, resulting in "true" profiles from the low-resolution measurements in satisfactory agreement with the high-resolution data which need not be corrected. For the weaker line at 3203 Å only the low-resolution measurements were possible, but the apparatus correction should be just as reliable. (Its main effect is to raise the central peak.) The line has again a near-Gaussian shape, except on the wings.

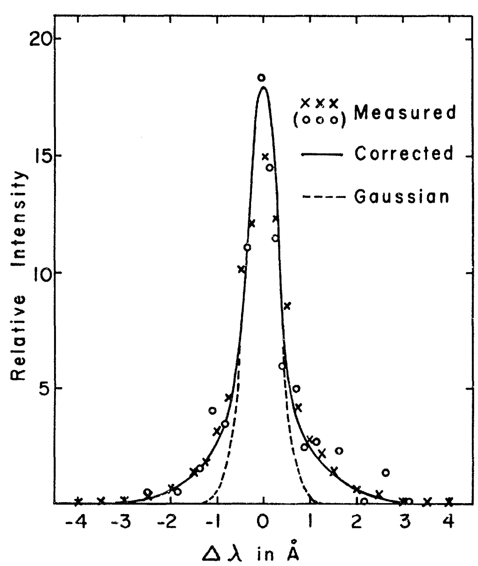

FIG. 1. Measured (first-order) and corrected profiles of the 4686-Å line and a Gaussian approximation. (Second-order data are represented by circles.)

As seen from Table I, measured linewidths (all corrected for apparatus broadening and in case of the first line averaged over high- and low-resolution results) are at early times in an opposite ratio from that expected for pure Doppler broadening. They do begin to approach this 1.45:1 ratio about 160 nsec later, when the current is small at the radius of observation. If the total width of the 4686-Å line is written as

$$\Delta\lambda_1 = [\Delta\lambda_{D1}'^2 + \Delta\lambda_{S1}^2]^{1/2} \tag{1}$$

in terms of its Doppler and (Gaussian) Stark widths, then that of the 3203-Å line is found to be consistent with

$$\Delta\lambda_2 = [\tfrac{1}{2}\Delta\lambda_{D1}'^2 + 2\Delta\lambda_{S1}^2]^{1/2}. \tag{2}$$

These parameters are also given in Table I and are believed to be accurate to ~±0.1 Å. (At this point, we make some allowance for fine structure by writing $\Delta\lambda_{D1}'^2 = \Delta\lambda_{D1}^2 + \Delta\lambda_{F1}^2$ with $\Delta\lambda_{F1} \approx 0.1$ Å and calculating the ion temperature from $\Delta\lambda_{D1}$. This correction is important only at 260 nsec.)

Whereas the factor $\frac{1}{2}$ in Eq. (2) is simply from the square of the wavelength ratio, the factor 2 requires some justification. A suitable mean value of the linear Stark effect for a line arising

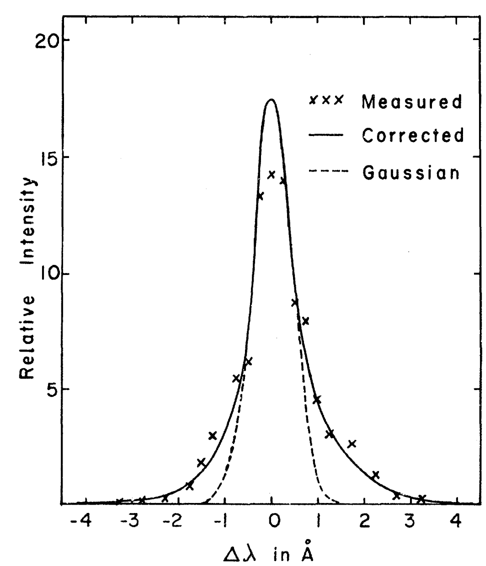

FIG. 2. Measured and corrected profiles of the 3203-Å line and a Gaussian approximation.

Table I. Total, Stark, and Doppler widths, rms field strengths,[a] and ion temperatures at various times.

t (nsec)	$\Delta\lambda_1$ (Å)	$\Delta\lambda_2$ (Å)	$\Delta\lambda_{S1}$ (Å)	$\Delta\lambda_{D1}'$ (Å)	$\langle F^2\rangle^{1/2}$ (kV/cm)	kT_i (eV)
260	0.75	1.00	0.70	0.30	18 ± 3	2.5 ± 2
320	0.75	0.80	0.50	0.55	13 ± 3	9 ± 3
420	0.65	0.50	0.15	0.60	4 ± 3	11 ± 4

[a]The indicated errors correspond to the estimated 0.1-Å experimental uncertainty in the widths. They do not allow for a possible systematic error of a factor ~1.5 in Eq. (5) nor for the non-Gaussian component (see Figs. 1 and 2), whose contribution to the total rms field strength is comparable with that of the Gaussian component calculated here.

from a transition $n \to n'$ is

$$\Delta\lambda_S \approx \frac{3}{4}\frac{(n^2-n'^2)\hbar\lambda^2}{2\pi Zmec}F, \tag{3}$$

with $Z=2$ for ionized helium; or, taking ratios,

$$\frac{\Delta\lambda_{S2}}{\Delta\lambda_{S1}} \approx \frac{5^2-3^2}{4^2-3^2}\left(\frac{\lambda_2}{\lambda_1}\right) \approx 1. \tag{4}$$

However, the $\lambda_1 \approx 4686$-Å line possesses an unshifted component having ~30% of its total intensity. This suggests that we multiply Eq. (3) by ~0.7, leading to the ratio adopted in Eq. (2) and to

$$\Delta\lambda_{S1} \approx 4\times10^{-2}\langle F^2\rangle^{1/2}\ \text{Å}, \tag{5}$$

if again a Gaussian distribution is assumed for the fields (in units kV/cm). Such a distribution is not only consistent with the measured line cores, but also expected for fully developed turbulence in one dimension. The weaker-than-Gaussian decay on the line wings cannot be explained by particle-produced fields either, i.e., the actual collective field distribution also has a component obeying, perhaps, an inverse power law. Finally, the direct correspondence between field strength distribution and line shape (quasistatic approximation) can be used because even the electron plasma frequency corresponds to wavelength separations near the half-widths.

The (Gaussian) rms field strengths of ≲20 kV/cm determined here agree satisfactorily with the theoretical estimates[6] discussed above and are consistent with the ≲10-kV/cm values estimated from plasma satellites[7-9] of neutral helium lines. These satellites, being essentially resonance phenonena, measure the dominant frequency components of the field, found[9] to be in the neighborhood of the ion plasma frequency from the position of the satellite, whereas the present method is sensitive to the whole spectrum near and below the electron plasma frequency.

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