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Stark shift of the He II P_α line in a dense plasma

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New measurements are reported on the red shift of the He II P_α line emitted from a gas-liner pinch plasma with electron densities in the range of $(1.0\text{–}2.4)\times 10^{18}$ cm^{-3} and electron temperatures between 5 and 7 eV. Line radiation was observed from a homogeneous and optically thin core region of the pinch discharge, free of impurity elements that could distort the line shape. The experimental shifts vary linearly with electron density and are in good agreement with calculations that we have performed on the basis of the classical-path and impact approximations for electron perturbers, according to the theory developed by Griem [Phys. Rev. A **27**, 2566 (1983); **38**, 2943 (1988)]. An important role is assigned in this work to the $\Delta n = 0$ interactions. Our calculations are also in good agreement with earlier measurements by Pittman and co-workers [Pittman *et al.*, Phys. Rev. Lett. **45**, 723 (1980)] and Fleurier and le Gall [J. Phys. B. **17**, 4311 (1984)]. The measured profiles of this line are entirely symmetrical within experimental error and show no evidence of an asymmetry favoring the blue wing.

INTRODUCTION

The λ4686 Å line of He II has long been of interest for spectroscopic studies of laboratory and astrophysical plasmas.[1–7] Since this line is subject to the linear Stark effect,[8–14] its appreciable broadening by the electric microfield in dense plasmas facilitates the study of other more subtle spectral features (e.g., line shift, possible red-blue asymmetry, and wavelength dependence in the wings[2,3]). In the course of establishing the width of this line as a primary diagnostic standard, interesting observations of a significant line shift have already been made.

While excellent agreement (within about 5%) was obtained by Berg and co-workers[15] between the measured width of the He II λ4686 Å line profile and the classical-path calculation by Griem and Shen,[1] a significant blue shift of the peak was claimed and explained on the basis of plasma polarization in the vicinity of the radiator. Subsequent work by Berg[16] on an improved shock-tube device yielded no experimental displacement of this line within ±0.3 Å up to electron densities of order 3×10^{17} cm^{-3}, but showed instead that impurity lines of common contaminant species such as Si III and O II can play a major role in producing spurious blue shifts and an apparent asymmetry in favor of the blue wing of this line. The theory of Griem and Shen[1] was confirmed by subsequent measurements of Bogen[17] on a small θ-pinch device, good agreement being obtained not only with the linewidths of Berg and co-workers[15] but also with the earlier wing measurements of Wulff.[14] The weight of subsequent observations has, after some controversy,[3,18,19] tended to reinforce these conclusions: A formula for the electron density in terms of the width of this line can be used as an accurate diagnostic standard[12,20,21] in the density regime $3\times 10^{16}\text{–}2.2\times 10^{18}$ cm^{-3}. The experimental linewidth calibrated by Thomson scattering[12] agrees best with the earliest classical-path calculation[1] and reasonably well with the later classical-path calculation of Kepple,[22] perhaps indicating the effective cancellation[19,23] of smaller ion dynamic[24] and upper–lower-state interference[3,25] effects.

While the situation regarding the linewidth now appears reasonably satisfactory, the same cannot be said of the line shift and possible red-blue asymmetry. Competing experimental claims have been made in recent years regarding both the nature and the extent of the central shift as a function of electron density[16,20,21,26–28] and the extent to which the blue wing of the line is enhanced above the red wing, if at all.[16,27,28] A number of theoretical models have also been proposed to account for the shift and asymmetry data, based upon the quadratic Stark effect from quasistatic ions,[3,29,30] quasistatic ion quadrupolar or field-gradient interactions,[31–33] plasma polarization in the neighborhood of the radiator at high electron densities,[3,15,26,34–36] quasimolecular satellites,[35] radiator-perturber quantum-interference effects,[35,37,38] quantum-scattering effects at small impact parameters,[39] plasma-radiator interactions within the framework of kinetic theory,[40] a self-consistent field model for the radiator embedded in a dense plasma with dynamical interactions,[41] the Baranger[42] electron-impact approximation evaluated for classical perturber trajectories,[30,43,44] or quantum mechanically[41,45] and last, various "trivial" sources of asymmetry.[2,30] However, as none of these models seemed capable of standing alone in providing a complete explanation of the observed phenomena, they have invariably been employed in various combinations of separate effects.[20,21,26–28,45,46] Much confusion has been generated in the literature by the multiplicity of such effects which are claimed to be significant.

In the present paper, we aim to extend the range of the shift data for the He II λ4686 Å line to higher electron densities than have hitherto been employed for these purposes, by using only stable, homogeneous, and welldiagnosed plasma conditions in the measurements. Thereby, we also show that the shift of this line can indeed be used as a secondary electron density diagnostic for dense plasmas to complement results from Stark width measurements.

EXPERIMENTAL CHARACTERISTICS AND METHOD

Any experiment designed for line-shift determinations should satisfy stringent requirements of plasma homogeneity, reproducibility, minimal opacity, and spectral purity in the wavelength region of interest.[34] The gas-liner pinch employed in this work complied very well with the stated requirements and was closely related to the version described previously.[12,23,27,47–51] Hydrogen was used as the driver gas, from which a hydrogen plasma was generated containing a small amount (of order 1%) of helium or nitrogen impurity (injected as test gas) in the center of the discharge column. Ultra-high-purity helium was employed. Line radiation from helium or nitrogen ions was shown by direct measurement to emanate from a small, approximately homogeneous, core region when observed at times near peak compression of the discharge. Self-absorption (radiative transfer) effects in both P_α and the nitrogen-ion lines employed for the density and temperature determination, respectively, were shown to be entirely negligible. Intensity ratios within nitrogen-ion multiplets shows the expected relationships,[52,53] and all observed intensities were of comparable order of magnitude, well below the corresponding blackbody level.[50] For reasons discussed below,[16] the pinch was operated in as clean a condition as possible, with minimal contamination by impurities. As shown previously by Thomson scattering measurements,[12] the electron- and proton-velocity distributions were free of turbulence at the times of measurement and corresponded to equal temperatures of these two major species. The ion impurity temperature could therefore be assumed equal to that of the electrons and protons, since the other proton ion equilibration time[54] (roughly 6 and 3 ns for He II and N IV ions, respectively) was much less than the implosion time (of order 100 ns).[51]

The various line profiles were recorded by an optical multichannel analyzer (OMA) system (SI), with a 1-m monochromator (Spex model 1704, planar grating with 600 lines/mm for P_α and 1200 lines/mm for nitrogen spectra). The instrumental profile was effectively Lorentzian, with a full width at half maximum (FWHM) of 1.1 Å (corresponding to 2.7 pixels at a reciprocal dispersion of 0.41 Å/pixel) for P_α and 0.25 Å for the nitrogen-ion lines, which were observed in second order. The data capture time for the OMA system was 30 ns, while the overall plasma lifetime was about 300 ns. Measurements were generally performed at or near the time of peak compression, the time settings being chosen with the aid of a continuum monitor centered at λ5200 Å. The wavelength of the optical system was calibrated with the aid of a Zn standard lamp.

The experimental width and corresponding shift of the P_α line as well as the nitrogen ion line widths were extracted with the aid of the simplex computational routine,[55] which incorporated the apparatus and Doppler profiles in the calculation.

DIAGNOSTIC PROCEDURE

The use of the full width (FWHM) of the P_α line profile in the determination of electron density has already been justified by comparison with Thomson scattering measurements,[12] and therefore this Stark-broadened line profile was again employed for these purposes in the present experiment. For the electron temperature determination, intensity ratios of N IV-to-N III lines were selected in preference to the use of carbon ion lines[12,27,50,51] in order to avoid unnecessary contamination of our spectra in the vicinity of the He II line under study. A very suitable pair of multiplets for this purpose was situated at λ4058 Å (N IV) and λ4100 Å (N III), respectively, with the obvious advantages of minimal calibration errors, and simultaneous display on the OMA screen in a single firing of the pinch. Details of the respective transitions are found in Table I, the necessary absorption oscillator strengths being calculated in the Coulomb approximation,[56] in excellent agreement with previously published values.[53,57] Such intensity ratios from successive ionization stages of nitrogen had earlier been used in spectroscopic studies of a θ-pinch plasma[57,58] at considerably lower electron densities in conjunction with a semicoronal model[2] for the level populations. In the present case, level populations were expected to be close to their LTE (Ref. 2) values for the particular N_e and T_e, noting in particular the important role of metastable levels[59] such as the $2p\ ^3P^0$ term in the berylliumlike system N IV in promoting the equilibration process. The minimum electron densities required for LTE of N III and N IV level populations in an optically thin plasma, according to various authors, have been tabulated[58,59] for somewhat lower temperatures than in the present experiment. While these values indicate that LTE should be a safe assumption for our plasma parame-

TABLE I. Nitrogen ion lines used in the electron temperature determination.

Ion	Wavelength (Å)	Multiplet	Transition	Oscillator strength (absorption)
N IV	4057.8	3	$3p\ ^1P^\circ_1-3d\ ^1D_2$	0.3226
N III	4097.3	1	$3s\ ^2S_{1/2}-3p\ ^2P^\circ_{3/2}$	0.4863
N III	4103.4	1	$3s\ ^2S_{1/2}-3p\ ^2P^\circ_{1/2}$	0.2428

ters, at least under nearly steady conditions,[2] we have determined our electron temperatures from the measured intensity ratios both with and without the assumption of LTE for N IV. We have also verified that the characteristic decay time of the N IV upper-level population is so small that possible deviations owing to transient behavior[2] could be ignored.

The semicoronal model for nitrogen was set up as follows. The low-lying (notably metastable) terms of the N IV system were assumed to be in LTE with the ground state, which was in turn treated as being in Saha-Boltzmann equilibrium with the upper levels of the N III lines in question. The population of the upper level of the N IV line was in turn obtained from the collisional-radiative balance equations linking it to the lower-lying levels, but ignoring for simplicity cascade from higher states. This procedure yielded the density-dependent correction to the LTE line-ratio formula,[2] whose deviation from the value of unity is given by the ratio of the sum of all Einstein coefficients (A values) to lower levels to the sum of all collisional deexcitation rates out of this N IV upper level. In the calculation of these collisional rates, approximate effective Gaunt factors for optically allowed $\Delta n \neq 0$ and $\Delta n = 0$ transitions were taken from Refs. 60 and 3, respectively, and average collision strengths for the optically forbidden (exchange and electric quadrupole) transitions from Ref. 61 for the isoelectronic system O V. The value employed for the quadrupole collision strength agrees within about 30% with the older measurement of Johnston and Kunze.[62] In any case, deviations of the semicoronal from the corresponding LTE line-ratio calculation, allowing also for the lowering of the ionization potential,[2] were minimal under the conditions of our experiment.

The temperature values have also been compared with those obtained from the intensity ratio of the C IV to C III line pair previously employed[12,51] after calibration against Thomson scattering. While the present temperature range is not very favorable for application of this line intensity ratio,[2] comparison with the nitrogen intensity ratio seems satisfactory, within the estimated error limits.

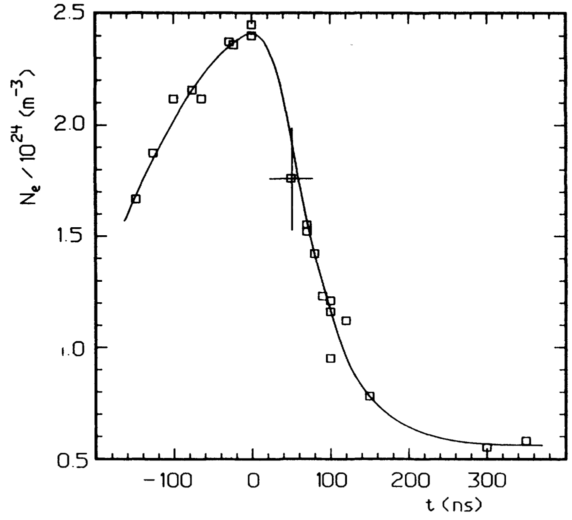

FIG. 1. Electron density N_e of the gas-liner pinch discharge as a function of time relative to peak compression.

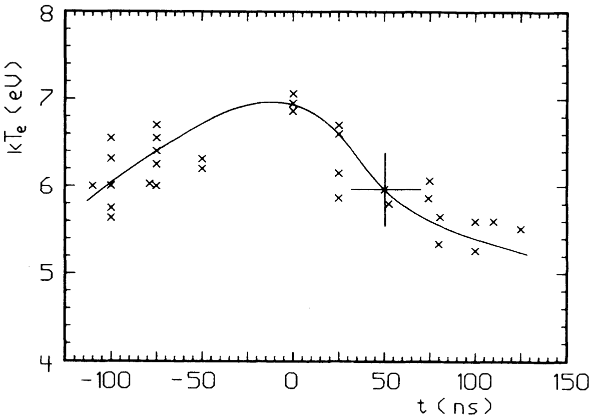

FIG. 2. Electron temperature kT_e of the gas-liner pinch plasma as a function of time relative to peak compression.

In Fig. 1 the electron density (N_e) is plotted as a function of time, starting from the compressional phase of the discharge until times in the expansion phase of order 400 ns beyond peak compression. Figure 2 shows the corresponding variation of electron temperature (kT_e) with time. A plot of $\log_{10}(N_e)$ versus $\log_{10}(T_e)$ in Fig. 3 is found to have the interesting feature of being quite linear in both compressional and expansion phases, except within a time interval of 50 ns around peak compression. This plot yields an effective adiabatic exponent of nearly $\frac{4}{3}$ in the expansion phase and is consistent with thermalization of the entire plasma only after 25 ns before peak compression.[54] Shift data were taken only at and after maximum compression.

Experimental error limits on the electron density and temperature were estimated to lie within 10% and 15%, respectively. These error limits account for the irrepro-

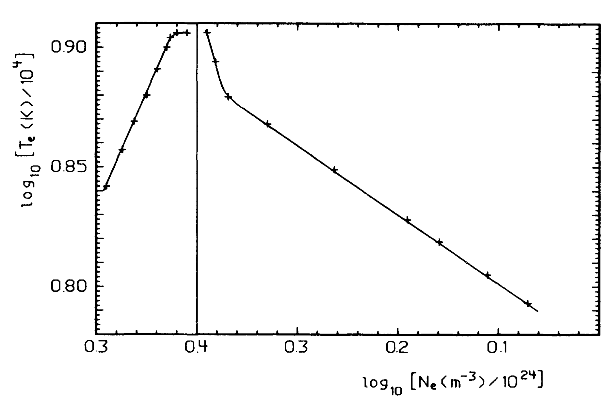

FIG. 3. Plot of $\log_{10}(N_e)$ vs $\log_{10}(T_e)$ in the compressional and expansion phases of the pinch discharge using the curves from Figs. 1 and 2.

ducibility of the pinch discharge as well as the uncertainties in the determination of line intensities and widths. The importance of the accuracy of the density determination for line shifts far exceeded that of the temperature determination (see below).

RESULTS AND DISCUSSION

A typical P_α spectrum, obtained from a single discharge, is shown in Fig. 4 together with the corresponding fit by the simplex routine,[55] from which the background continuum radiation has been subtracted, with allowance for its wavelength dependence. By observation of this spectral region without helium test gas present, we were able to confirm the spectral purity of the underlying hydrogen continuum. The ripple on the line profile and continuum is rather small and consists of noise together with intensity fluctuations related to fluctuations in the plasma density and temperature.[63] It should be particularly noted that the P_α line profiles obtained in this work were within experimental error entirely symmetrical. Since no evidence was obtained for asymmetry favoring the blue wing,[27,28] we have taken this observation as *prima facie* evidence of the spectral purity of our plasma[16] and accordingly determined the line shifts with respect to the peak of the profile (note the absence of opacity effects, as discussed above). After completion of the experiment with nitrogen as the test gas, we introduced methane for additional temperature measurements from carbon ion line ratios (see above). The effect of carbon impurity lines on the blue wing of the P_α line was immediately apparent, as a demonstration of the role of residual carbon contamination in producing spurious asymmetries.

In order to verify that the observed line radiation from the test gas indeed emanated from a relatively homogeneous, central region of small radius, observations were carried out on the He II B_α line (λ1640 Å) and the underlying continuum along sections through the discharge column displaced by various distances from the central axis. The vuv instrumentation used is described in Ref. 23. The results displayed in Fig. 5 show the relatively sharp confinement of the test-gas radiation to the hot-core region.

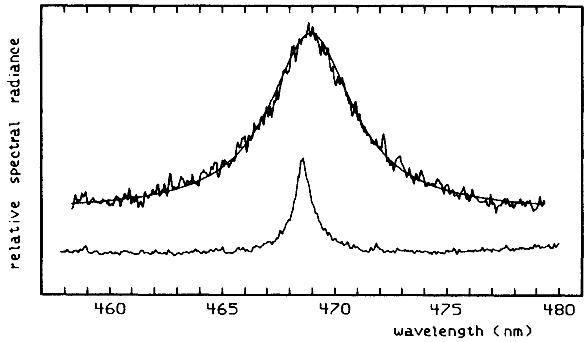

FIG. 4. A typical He II P_α line profile near maximum compression and in the afterglow stage (time 0.8 μs) of the pinch discharge. The red shift at high electron densities is obvious. The two profiles have been plotted on different scales of spectral radiance.

Results obtained for the experimental Stark shift of the line center of P_α as a function of N_e and kT_e are shown in Fig. 6. The line shifts were obtained with the aid of the Zn lamp calibration and by observation of the much narrower line spectra in the afterglow stage of the decaying plasma (Fig. 4).

Theoretical shifts of this line were calculated in the classical-path[1-3] and impact[42] approximations as applied to electron perturbers according to the treatment by Griem[3,30,43] with some small refinements of the computational technique and including also the mixing of degenerate-radiator states by the plasma microfield. The calculations may be briefly summarized as follows. Dealing first with the $\Delta n = 0$ interactions, we have used the more general expression for the line shift in Ref. 30 (derived from the work of Boercker and Iglesias[40]), i.e., the form leading to Eq. (13) (for $Z = 2$) rather than Eq. (15) (of Ref. 30) but introducing also a factor of 1.2 for strong collision contributions. The $\Delta n = 0$ contributions are found to play an even more important role in the present work than in Ref. 30, particularly for temperatures below 5 eV. The $\Delta n \neq 0$ shift contributions[3,43] include those arising from elastic and weak inelastic collisions. For the latter, the unitarization procedure is introduced for each partial-wave (perturber angular momentum) contribution, and strong collision contributions enter through the cutoff to the phase shift for electric dipole interactions. Characteristic dipole-shift functions are tabulated in Ref. 3, and additional values for small δ/ξ are obtained from the analysis by Klarsfeld.[64] Both electric dipole and quadrupole contributions are included for all perturbing

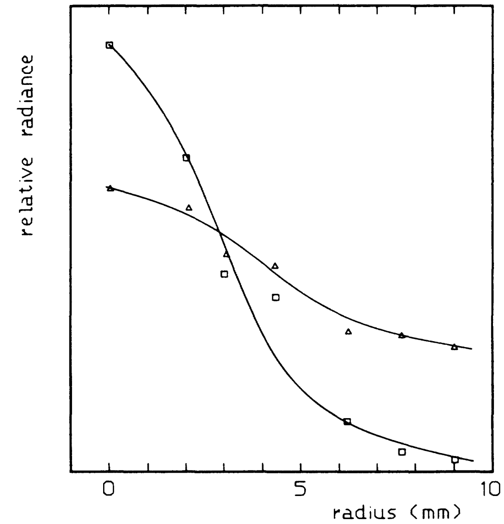

FIG. 5. Wavelength-integrated relative radiance of the He II B_α line □ and the underlying continuum △ vs radius of the plasma column at maximum compression. The spectral radiance scales are the same for both profiles.

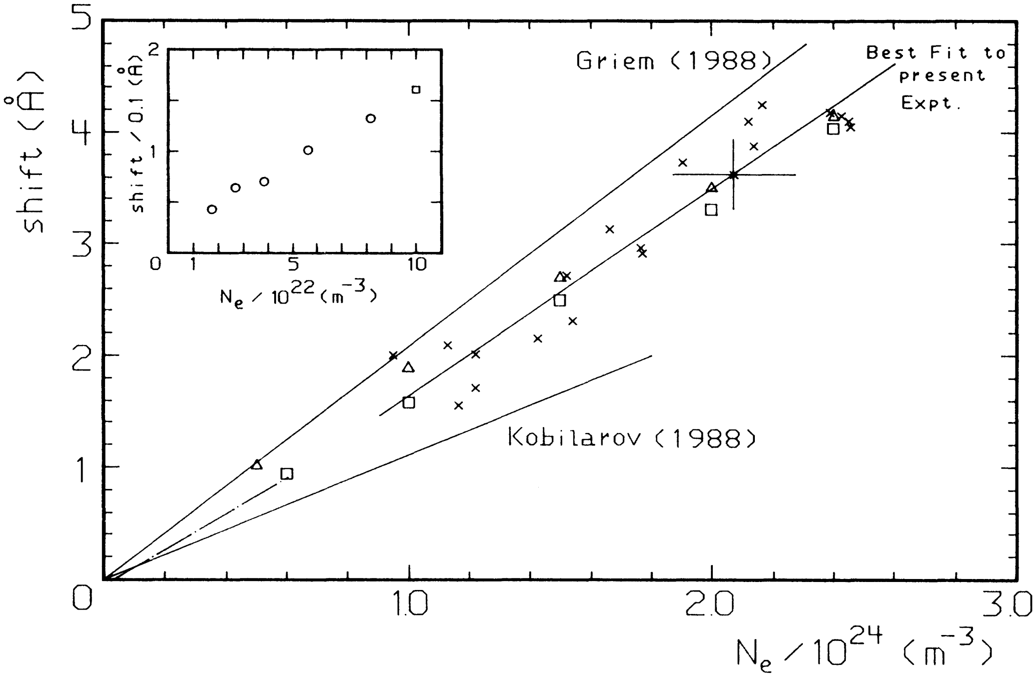

FIG. 6. Comparison of various shift measurements of the He II P_α line with theory as a function of electron density N_e. Measurements: ——, Kobilarov *et al.* (Ref. 28); —·—·—·, Fleurier *et al.* (Ref. 20); × × ×, present measurements. Theory: ——, Griem (Ref. 30) (electron-impact shifts); △△, Nguyen *et al.* (Ref. 41), for the plasma parameters 0.5×10^{24} m^{-3}, 4.0 eV; 1.0×10^{24} m^{-3}, 5.0 eV; 1.5×10^{24} m^{-3}, 5.9 eV; 2.0×10^{24} m^{-3}, 6.5 eV; 2.4×10^{24} m^{-3}, 7.0 eV; □□, present calculations for the plasma parameters 0.6×10^{24} m^{-3}, 4.0 eV; 1.0×10^{24} m^{-3}, 5.0 eV; 1.5×10^{24} m^{-3}, 5.9 eV; 2.0×10^{24} m^{-3}, 6.5 eV; 2.4×10^{24} m^{-3}, 7.0 eV. The inset includes measurements by Pittman *et al.* (Ref. 26), ○ and the present theory □ for $N_e=1.0\times10^{23}$ m^{-3} and $kT_e=3.73$ eV.

levels n' up to a cutoff, which omits levels whose dipole-shift contribution is less than 10% of that of the major perturbing level. (Use of a much more stringent cutoff procedure showed that the above criterion produces a negligible computational error because of the rather rapid decrease in shift contribution with increasing separation between levels n and n'.) Values for the characteristic quadrupole shift functions are again obtained from Ref. 3, but an improved version of Eq. (13) of Ref. 43 is employed, which removes the velocity singularity in that relation. (This would enhance the quadrupole-shift contributions quite unnaturally in the below-threshold velocity region.) In the integration over impact parameters (in effect therefore over perturber angular momenta), the lower cutoff is introduced exactly as in Ref. 43, but instead of infinity at the upper limit of integration, we have used the Spitzer[65] adiabatic cutoff for slow traversals. The treatment of the perturber trajectory (path elements) then follows as in Refs. 66–69 with the elastic contributions from perturbation theory [see Eq. (12) of Ref. 43] determined corresponding to the upper cutoff parameters. In practice this departure from the method used in Ref. 43 is not of primary importance, since effective convergence of the integrals in that paper was already obtained by twice to four times the minimum perturber angular momentum. The present procedure is satisfactory from a theoretical standpoint, however, since the below-threshold velocity region now yields only two types of (elastic) contributions: those corresponding to the elastic terms mentioned above and those corresponding to extrapolation of the weak inelastic terms.[70] The procedure is thus consistent with that normally employed in calculations of the semiclassical effective Gaunt factors for the linewidth.[3,66–69]

It must be admitted, however, that this line-shift model still has certain inherent limitations and associated uncertainties, some of which are discussed in the literature.[3,30,43] A distinction is, therefore, necessary between the comparatively high precision of the present calculations and their actual accuracy, owing to the sensitivity of individual shift contributions to the simplifying assumptions incorporated in the treatment. One major simplifying assumption lies in the application of the theory for the $\Delta n=0$ interactions[40] to charged radiators, without account being taken of the plasma polarization shift. Possibly important lowest-order shift contributions arising from static initial correlations[3] of charged perturbers in the vicinity of each radiator are thereby ignored. A brief discussion of the significance of this omission is given by Boercker and Iglesias,[40] as well as by Griem.[30] A very wide divergence, both in magnitude and sign, between existing theories for the plasma polarization shift in the literature,[3,15,26,34–36] should, however, be pointed out. Another simplification lies in the neglect of quasistatic ion quadrupolar shifts, which have been evaluated in some detail by Griem,[30,43] together with the corresponding quadratic ion contributions. While ion dynamical effects should be small at our electron densities,[3] they might well lead to an increase in the estimated values of these contributions.[30] The breakdown of the quasistatic approximation for ion perturbers in the central region of the line profile has been considered by Griem.[30]

Comparison between the measurements and our calculations is shown in Fig. 6, together with other recent experimental results[20,26,28] and the theoretical values published by Griem[30] (given here for electron impact shifts only). The table for the hydrogenic line-shift factor according to the self-consistent field, quantum-mechanical calculations of Nguyen and co-workers[41] has also been applied (with allowance for mixing of degenerate unperturbed hydrogenic states by the plasma microfield) to the case of He II P_α and the results shown in the figure. Agreement between the regression analysis of our measured data and our calculations is good, well within the limits of experimental error. The experimental values in Refs. 21 and 28 lie rather significantly below ours. Agreement (after extrapolation to lower electron densities) with older experimental values[20,26] is indeed much better (see insert to Fig. 6 and below). Whereas our results indicate a weak overall temperature dependence, the quantum-mechanical values, while also showing very good overall agreement, are more temperature sensitive. This comparison indicates that penetrating monopole collisions,[41] which we have ignored, perhaps do not play a dominant role in the present case.

The total theoretical red shift has been parametrized by the following compact formula (which accounts for mixing of degenerate radiator states by the plasma microfield):

$$\Delta\lambda\,(\text{Å}) = 10^{-18} N_e \left[\frac{1}{(kT_e)^2} + \frac{kT_e}{16} + \frac{5}{4} \right]$$

with N_e in cm^{-3}, and kT_e in eV. This relation is certainly valid only in the low-temperature regime ($kT_e \lesssim 9$ eV).

It is important to note that the quasistatic ion quadrupole interaction[32] (excluding small corrections for Debye shielding and ion-ion correlations[24]) would yield an enhancement of the red wing relative to the blue but that this is apparently effectively compensated by trivial sources[2,30] of asymmetry.

As regards observations of an enhancement of the blue wing of He II P_α,[27,28] the crucial role of carbon and oxygen ion impurity lines should be pointed out. Some of these lie in the immediate vicinity of the peak towards the blue and would not only tend to produce such an apparent distortion of the true line profile but to reduce the observed shift measurably.

CONCLUSIONS

The following conclusions may be drawn from the present study of the He II P_α line.

(i) The line profile is within experimental error symmetrically broadened by the electric microfield in plasmas up to an electron density of $2.4\times10^{18}\ \text{cm}^{-3}$. Since trivial sources of asymmetry would tend to favor the blue wing, these are apparently effectively compensated by the quasistatic quadrupolar or field-gradient interactions in the wings. Previous observations of asymmetries favoring the blue could plausibly have been due to the presence of moderately strong impurity lines, as was already shown by Berg.[16]

(ii) A good account of the measured red shift of line center, which is within experimental error proportional to N_e and only weakly dependent upon T_e, is given by a calculation based upon the classical-path and impact approximations applied to electron perturbers.[30,43] This calculation assigns an important role to the interactions for which $\Delta n = 0$. Agreement between experiment and theory in our case suggests that the electron-impact shift is a major shift mechanism at high electron densities. Because of the sensitivity of the Stark shift to many different physical processes of various magnitude and sign, however, the reader is cautioned not to interpret this agreement as proof that a unique shift mechanism is operative in a plasma of the type considered in this work. Possibly important processes which we have not explicitly accounted for here are those associated with plasma polarization and ion-quadrupole interactions.

(iii) In order to facilitate comparison between the present paper and future experimental work, a formula for the shift of the He II P_α line is given above as function of the plasma parameters. This formula yields an excellent fit to our theoretical values in the indicated parameter ranges.

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APPENDIX

Application of Eq. (15) of Ref. 3, shows that when single-proton perturber-radiator interactions are considered, dynamical effects on the broadening of He II P_α will start to operate within some 5 Å of line center. This estimate concerns first the linear Stark effect. It is further argued[3] that the simultaneous interaction of two or more perturbers will significantly smooth the field fluctuations, permitting the relaxation of a more stringent requirement on the minimum perturber density necessary for application of the quasistatic approximation throughout most of the line profile. It is now known, however, that appreciable ion dynamical effects can occur near line center at electron densities in excess of the threshold value predicted by Eq. (17) of Ref. 3 (see, for example, the literature cited in Ref. 24). Our present concern, however, is not with the importance of dynamical effects on the ion-produced broadening through the linear Stark effect at the rather high electron densities in the present experiment. It is rather to suggest that only rather small ion dynamical effects in first order could significantly influence the assumed line broadening (shift) mechanism in the next order beyond linear, i.e., ion quadrupolar, in the region around line center.

We note again that for a quasistatic treatment to hold, the inverse of the time scale T for the radiator-perturber interaction should be significantly less than the corresponding displacement ($\Delta\omega_k$) of the Stark component in question:[3]

$$T^{-1} \ll |\Delta\omega_k| \ . \tag{A1}$$

For a central component of the line undisplaced in first order, we write[32] for the shift through the ion-quadrupole interaction

$$\Delta\omega_k = \frac{3}{2}\left[\frac{Z_p}{Z^2}\right]\alpha c\left[\frac{a_0^2}{R^3}\right]\Delta_k^q(n,n') \ , \tag{A2}$$

where

$$\Delta_k^q(n,n') = \tfrac{1}{3}(n^4 - n^2 - n'^4 + n'^2) \ . \tag{A3}$$

Here Z_p denotes the ion perturber charge, $Z=2$ the ionization stage of the radiator, α the fine-structure constant, a_0 the Bohr radius, and R the radiator-perturber separation.

For a typical perturber situated at a distance near the mean interperturber radius,[3] one immediately obtains a threshold density (N_p) required in order to treat the perturber as static. It may now be asked to what extent perturber correlations will reduce this lower limit on N_p. This may be estimated with the aid of the many-body correction to the nearest-neighbor field gradient, denoted as $T_0(\beta)$.[24,26,33,43] This is expressed in terms of the Holtsmark function $H(\beta)$ and its integral $K(\beta)$ by

$$T_0(\beta) = \tfrac{15}{8}\sqrt{(2/\pi)}\,\beta^{-5/2}[K(\beta) - \beta H(\beta)/3]/H(\beta) \ , \tag{A4}$$

where β denotes the field strength in units of the Holtsmark normal field strength F_0.

These considerations yield as an estimate of the lower threshold-perturber density required for the quasistatic regime to hold in line center

$$N_p \gtrsim \frac{Z^3}{Z_p^{3/2}}\left[\frac{m_e k T_e}{\mu_r E_H}\right]^{3/4} a_0^{-3}\left[\frac{T_0(\beta)}{\Delta_k^q(n,n')}\right]^{3/2} , \tag{A5}$$

where T_0 should be evaluated for a β value of about unity and m_e, μ_r, and E_H denote the electron mass, reduced mass of the perturber-radiator pair, and Rydberg unit of energy, respectively.

Although only a rather rough approximation since the relative importance of the "unshifted" central component to the line profile as a whole has not been accounted for, the above formula nevertheless yields a threshold perturber density in excess of 10^{19} cm^{-3} for typical plasma temperatures of present interest, i.e., above our maximum electron densities by a rather safe margin. The inference is therefore suggested that calculations of the line shift and central asymmetry from quasistatic ion interactions should be employed with caution under the present experimental conditions, owing to dynamical effects in the line center. The same considerations perhaps therefore apply also to the weaker quadratic ion contributions.[30,32]

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