Stark broadening of the B III $2s$-$2p$ lines

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We present a quantum-mechanical calculation of Stark linewidths from electron-ion collisions for the $2s_{1/2}$-$2p_{1/2,3/2}$, $\lambda = 2066$ and 2067 Å, resonance transitions in B III. The results confirm previous quantum-mechanical R-matrix calculations, but contradict recent measurements and semiclassical and some semiempirical calculations. The differences between the calculations can be attributed to the dominance of small L partial waves in the electron-atom scattering, while the large Stark widths inferred from the measurements would be substantially reduced if allowance is made for hydrodynamic turbulence from high-Reynolds-number flows and the associated Doppler broadening. [S1063-651X(97)09612-8]

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I. INTRODUCTION

The Stark broadening of spectral lines is due to interactions of the emitting atom (ion) with electrons and ions in a plasma [1]. The resulting line profiles can serve as an important tool for plasma diagnostics in a very broad range of plasma parameters. It should be emphasized, however, that Stark broadening diagnostics generally require quite elaborate calculations. Therefore, comparison of theoretical line profiles with the Stark widths measured for well determined plasma conditions is very important for the improvement of theoretical approximations and techniques.

Recently, accurate line profile measurements of the $2s$-$2p$ fine-structure components of the resonance doublet in Li-like boron were performed by Glenzer and Kunze [2]. They used a homogeneous plasma region in a gas-liner pinch discharge, and plasma parameters, such as local electron density and ion temperature, were independently determined by 90° collective Thomson scattering. The Stark linewidths were measured to be $w \simeq 0.22$ Å for an electron density $N_e = 1.8 \times 10^{18}$ cm^{-3} and temperatures $T_i = T_e = 10.6$ eV. This value of w is within 25% of the results of semiempirical [1,3] and semiclassical [4,5] calculations, and exceeds the quantum-mechanical R-matrix calculations [6] almost by a factor of 2. A similar discrepancy between measurements and quantum-mechanical calculations had been noted previously for $2s$-$2p$ resonance transitions in another Li-like ion, namely, Be II [7].

In this paper we calculate the Stark linewidth of the $2s$-$2p$ transitions in B III. In Sec. II the theoretical approach and atomic data used in our calculations are presented. Then, in Sec. III, we present results and discuss the reasons for differences between quantum-mechanical and other calculations as well as experiment. Finally, Sec. IV contains conclusions and suggestions.

II. THEORY

As was shown by Baranger [8], for an isolated line corresponding to a transition $u \rightarrow l$ the full collisional width at half-maximum (FWHM) is given by

$$w = N_e \int_0^\infty vF(v) \left(\sum_{u' \neq u} \sigma_{uu'}(v) + \sum_{l' \neq l} \sigma_{ll'}(v) + \int |f_u(\theta,v) - f_l(\theta,v)|^2 d\Omega \right) dv, \quad (1)$$

where N_e is the electron density, v is the velocity of the scattering electron, and $F(v)$ is the Maxwellian electron velocity distribution. The electron impact cross sections $\sigma_{uu'}(\sigma_{ll'})$ represent contributions from transitions connecting the upper (lower) level with other perturbing levels (indicated by primes). In Eq. (1), $f_u(\theta,v)$ and $f_l(\theta,v)$ are elastic scattering amplitudes for the target ion in the upper and lower states, respectively, and the integral is performed over the scattering angle θ, with $d\Omega$ being the element of solid angle. Equation (1) relates a linewidth in the impact approximation with atomic cross sections, facilitating the use of well-developed techniques of atomic scattering calculations for line broadening studies. The inelastic terms account for broadening due to lifetime shortening, i.e., broadening associated with decaying amplitudes of the emitted waves. The elastic terms are due to phase shifts between wave trains before and after collisions; these phase shifts arise from the differences in perturbations of upper and lower levels.

The electron impact broadening of the $2s$-$2p$ principal resonance lines in Li-like ions differs from the broadening of other lines (like, e.g., $3s$-$3p$) due to the specific level structure of Li-like ions. Both initial and final levels of this transition are well separated from the other excited levels, the energy difference between $2s$ and $2p$ states being much

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smaller than the energy gap to the nearest $n=3$ level [in B III $\Delta E(2s\text{-}2p)\approx 6.0$ eV, while $\Delta E(2p\text{-}3s)\approx 16.3$ eV]. Hence, the $\Delta n \geqslant 1$ inelastic collisions are only marginally important for the broadening of this line. Additionally, the temperature of maximal abundance of B III in plasmas is a few times smaller than its ionization potential 37.9 eV, unless the plasma is rapidly ionizing. Therefore, it is hardly possible to have B III resonance lines in high-temperature, high-density plasmas where inelastic perturbations due to interactions with $n \geqslant 3$ levels would become important.

Quite surprisingly, practically no accurate atomic data were available for B III until very recently. The evaluated bibliographic compilation of electron impact excitation cross sections for ions [9] contains only *one* paper on B III, with poor accuracy. This differs drastically from the other members of the Li-like sequence (Be II, C IV, etc.), where, on the average more than 15 papers were published for each ion, some calculations being claimed to be accurate to within 10%. Fortunately, very accurate results for excitation cross sections from the ground state of B III have recently been achieved [10]. They were obtained with two new methods in atomic collision theory, viz., convergent close coupling (CCC) [11,12] and R matrix with pseudostates (RMPS) [13], which proved to be very successful in calculations of electron scattering on quasi-one-electron ions (see, e.g., Ref. [14]). Although the CCC and RMPS methods are quite close in principle, the agreement of *independently* obtained results which are separately checked for convergence in coordinate and momentum subspaces is a very convincing argument for these data to be accurate. The CCC method is a standard close-coupling approach where all target states (discrete and continuum) are obtained by diagonalizing the Hamiltonian in a large orthogonal Laguerre basis, and the coupled equations are formulated in momentum space. Therefore, the convergence can be easily tested by simply increasing the basis size. The use of momentum space allows one to avoid the common difficulties related to the oscillating behavior of wave functions in coordinate space. The RMPS method [13] is a modification of the standard low-energy R-matrix approach [15], where a much larger number of pseudo-orbitals is taken into account. This significantly improves the description of both the physical target states and highly excited and continuum pseudostates. For details on these methods see, e.g., Refs. [13,16].

For calculations of $2l$-$3l'$ and $2l$-$4l''$ cross sections, which are relatively small, we used the Coulomb-Born-exchange (CBE) code ATOM (the details of the basic approximations can be found in Ref. [17]). It should be noted that in addition to accounting for Coulomb attraction and exchange effects, ATOM calculates inelastic cross sections with *experimental* energy differences between the states involved, and allows for normalization (unitarity) effects. Unlike more sophisticated and time-consuming CCC and RMPS codes running at least on workstations, ATOM quickly generates many cross sections on a modest personal computer, which makes it especially suitable for large-scale collisional calculations. Although the application of the CBE method to a relatively low charge ion such as B III may be questioned, the difference between the ATOM and CCC-RMPS cross sections is mostly only about 30% at threshold. (For highly charged Li-like ions, the CBE and CCC results agree much better with each other [18].)

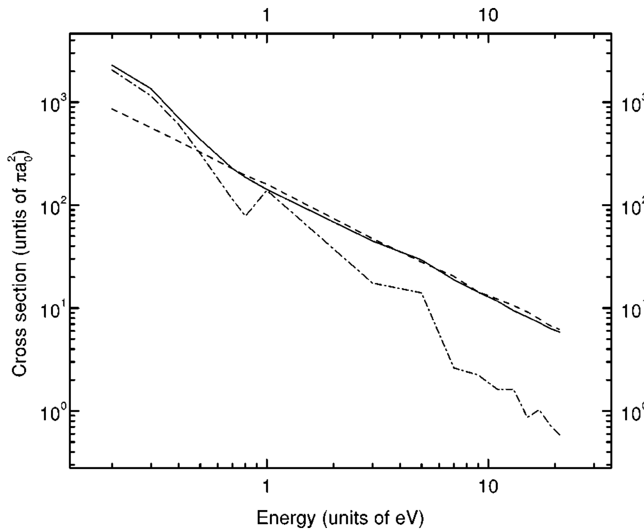

FIG. 1. Non-Coulomb elastic cross sections from the $2s$ (solid line) and $2p$ (dashed line) states of B III vs electron energy E. The elastic difference term $\widetilde{\sigma}(E)$ is shown by the dot-dashed line.

A. $2s$ and $2p$ effects

1. Elastic collisions

The non-Coulomb elastic scattering amplitudes $f_{2s}(\theta,v)$ and $f_{2p}(\theta,v)$ were calculated with the CCC method. The corresponding elastic cross sections $\sigma_{2s}(E)$ and $\sigma_{2p}(E)$, as well as the elastic difference term $\widetilde{\sigma}(E)\equiv\int|f_{2s}(\theta,v) - f_{2p}(\theta,v)|^2 d\Omega$, are presented in Fig. 1 as a function of the electron energy in the range $E=0.2$–21 eV. One can see a noticeable difference in the energy dependence of these parameters. While $\sigma_{2s}(E)$ and $\sigma_{2p}(E)$ approximately behave as $1/E$, the elastic term $\widetilde{\sigma}(E)$ decreases much faster, so that for *this* energy region it can be well fitted by the function $1/E^{\alpha}$ with $\alpha \simeq 1.8$ [for the smallest energies $\widetilde{\sigma}(E) \sim \sigma_{2s}(E)$ since, as is seen from Fig. 1, $\sigma_{2p}(E) \ll \sigma_{2s}(E)$ at $E \rightarrow 0$]. The contribution of the elastic term to the linewidth at $N_e = 1.8 \times 10^{18}$ cm^{-3} and $T_e = 10.6$ eV is $w_{\rm el} \approx 0.035$ Å, whereas simply using the sum of the elastic cross sections would give $w_{\rm el} \approx 0.20$ Å. Due to this cancellation, there may therefore be more uncertainty in $w_{\rm el}$ than in the following calculation of inelastic contributions.

2. Inelastic collisions

The $2s$-$2p$ excitation cross section calculated by various methods is shown in Fig. 2 as a function of the incoming electron energy. One can see that contributions of resonances to this cross section are very moderate. It should be noted also that even at threshold the electron exchange contributes not more than 10% of the total cross section. For small energies the CBE cross sections lie systematically above the RMPS result, but the difference is only 20% near the energy of interest. As the semiempirical Van Regemorter formula for excitation cross sections (see, e.g., Ref. [9])

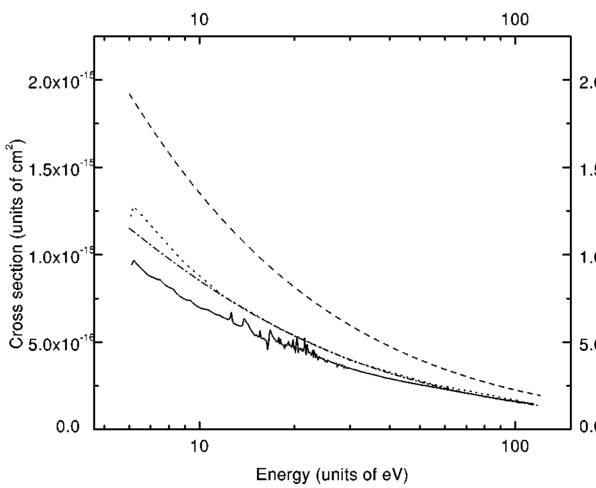

FIG. 2. Excitation cross section for the B III $2s$-$2p$ transition as a function of electron energy: —, R matrix with pseudostates [10]; ⋯, Coulomb-Born exchange (Sec. II); -·-, semiempirical Van Regemorter cross section according to Eq. (2) with Gaunt factor after Ref. [19]; ---, semiempirical Van Regemorter cross section with Gaunt factor after Ref. [20].

$$\sigma_{se}(E)=\pi a_0^2 f_{ul}\,\frac{8\pi}{\sqrt{3}}\,\frac{\mathcal{R}^2}{\Delta E}\,\frac{\overline{g(E)}}{E} \tag{2}$$

is often used in line broadening calculations, we also show two cross sections obtained with different choices of the effective Gaunt factor $\overline{g(E)}$. In Eq. (2), $a_0=0.529\times10^{-8}$ cm is the Bohr radius, f_{ul} is the absorption oscillator strength, ΔE is the energy difference, and the Rydberg constant $\mathcal{R}=13.61$ eV. For an absorption oscillator strength of $f_{2p\text{-}2s}=0.365$ and the $\Delta n=0$ Gaunt factor [19]

$$\overline{g(E)}=\left(1-\frac{1}{Z}\right)\left(0.7+\frac{1}{n_l}\right)\left[0.6+\frac{\sqrt{3}}{2\pi}\ln\left(\frac{E}{\Delta E}\right)\right], \tag{3}$$

with Z being the spectroscopic charge and n_l the principal quantum number of the lower level, the corresponding cross section is quite accurate for not too high energies (dot-dashed line in Fig. 2), while the Gaunt factor

$$\overline{g(E)}\simeq0.8+\frac{\sqrt{3}}{2\pi}\ln\left(\frac{E}{\Delta E}\right) \tag{4}$$

recommended in Ref. [20] (dashed line on Fig. 2) leads at low energies to an overestimation of the cross section by a factor of 2. This clearly demonstrates that one should be very cautious when choosing a specific form of the Gaunt factor. [Measurements of near threshold cross sections and excitation rate coefficients for C IV [21] also favor Eq. (3) for $\overline{g}$, while earlier plasma measurements [22] for N V, O VI, and Ne VIII at temperatures well above ΔE give effective Gaunt factors that are mostly smaller than those according to Eqs. (3) and (4) by factors 1.5 to 2.]

In Fig. 3 we present the ratio of the sum of partial cross sections with angular momentum $L\leqslant L_T$ to the total $2s$-$2p$ excitation cross section at $E=10$ eV calculated with the CCC and CBE methods (here L_T is the total angular momentum of the system ion plus electron). Remarkably, both approximations show very similar behavior for this ratio, with slight deviations for very low L_T. It is obvious that the major contribution comes from rather small L partial waves, so that the partial cross sections with total angular momentum up to $L_T=4$ give more than 60% of the total cross section. Even smaller L values dominate the elastic scattering contribution for which monopole $(\Lambda=0)$ contributions are very important.

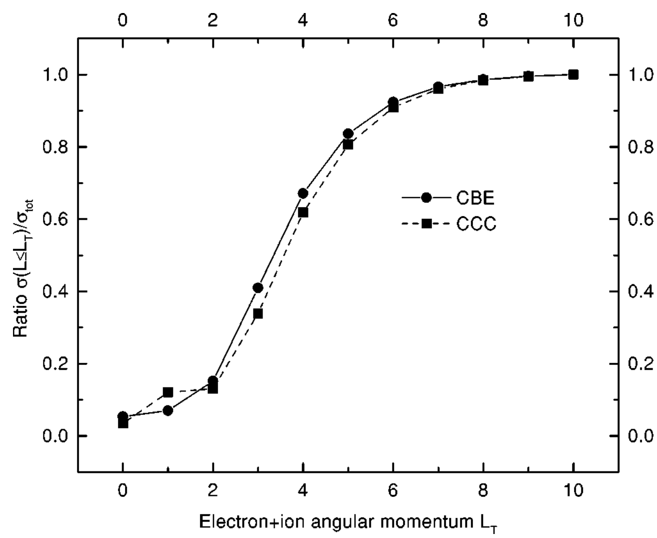

FIG. 3. Ratio of the sum of partial cross sections with angular momentum $L\leqslant L_T$ to the total excitation cross section for the B III $2s$-$2p$ transition vs angular momentum L_T.

To summarize, for an electron density $N_e=1.8\times10^{18}$ cm^{-3} and an electron temperature $T_e=10.6$ eV the contribution of the $2s$-$2p$ inelastic transitions, i.e., of excitation and deexcitation, to the linewidth is $w_{\text{in}}(\Delta n=0)\approx0.062$ Å. The CBE method gives $w_{\text{in}}(\Delta n=0)\approx0.075$ Å, which is only about 20% higher.

B. Inelastic $\Delta n\geqslant1$ collisions

The inelastic cross sections for the $2l$-$3l'$ and $2l$-$4l''$ transitions were calculated with the CBE code ATOM with no resonances included. Although resonances in the excitation cross sections are more important for $\Delta n\neq0$ transitions that for $2s$-$2p$ [10], the contribution of the 2-3 and 2-4 inelastic channels to the total linewidth is, in fact, rather small. Besides, the comparison of the RMPS and CBE $2s$-$3l$ excitation cross sections shows that the inelastic rate coefficients $\langle\sigma v\rangle_{2\text{-}3}$ produced with ATOM differ by about 20% on the average. This accuracy seems to be quite acceptable since the contribution of $2l$-$3l'$ inelastic transitions to the Stark linewidth is only $w_{\text{in}}(\Delta n=1)\approx0.005$ Å. Finally, the contribution of the $2l$-$4l''$ transitions is one order of magnitude smaller.

Generally, in addition to the electron impact excitation and deexcitation, other processes of plasma particle scattering from the upper and lower levels should be taken into account as well. Our CBE estimates and the CCC-RMPS data [10] show that, for the $2s$-$2p$ line, electron impact ionization and recombination can be safely neglected for the plasma parameters of Ref. [2]. Recent semiclassical results [4] indicate that ion-ion collisions may contribute up to 10% to the total Stark width, but most calculations cited below do not take this effect into account.

TABLE I. Ratio of experimental Stark width [2] of the $2s$-$2p$ line in B III to different theoretical widths.

T_e (eV)	N_e (cm^{-3})	w_{expt}/w_{theor}						
10.6	1.81×10^{18}	1.2[a]	1.2[b]	1.1[c]	1.0[d]	1.8[e]	2.1[f]	1.9[g]

[a]Semiempirical [1].
[b]Semiempirical [3].
[c]Semiclassical [4].
[d]Semiclassical [5].
[e]R matrix [6].
[f]CCC method (present work).
[g]CBE method (present work).

III. DISCUSSIONS AND SUGGESTIONS

The sum of all electron collisional contributions to the FWHM calculated here is

$$w=w_{el}+w_{in}(\Delta n=0)+w_{in}(\Delta n\neq 0)\approx 0.104\ \text{Å} \tag{5}$$

for an electron temperature of $T_e=10.6$ eV and an electron density of $N_e=1.8\times10^{18}$ cm^{-3}. In Table I we compare the experimental linewidth w_{expt} [2] with different theoretical calculations [1,3–6]. The two last columns in this table present the results of our calculations, viz., the next to the last column corresponds to Eq. (5), while the linewidth in the last column was obtained with CBE for all inelastic cross sections and the elastic term from CCC. The available B III $2s$-$2p$ Stark widths are also shown in Fig. 4 as a function of electron temperature. Our calculations presented here agree with the R-matrix results of Seaton [6] practically for all temperatures, thereby confirming the discrepancy with experiment. The 20% difference in CCC and R-matrix linewidths for very small T_e, where elastic collisions dominate, seems to be related to the strong cancellation effects in the scattering amplitude difference (see Sec. II). On the other hand, the latest semiclassical calculations [4,5] do agree with the previous results obtained with similar methods [1,3] as well as with the measured value of the linewidth, although for small T_e the results of Dimitrijević and Sahal-Brechot [4] deviate significantly from the other calculations. We also show modified semiempirical results [23] which, although calculated only up to ~ 7 eV, are very close to both sets of quantum-mechanical calculations.

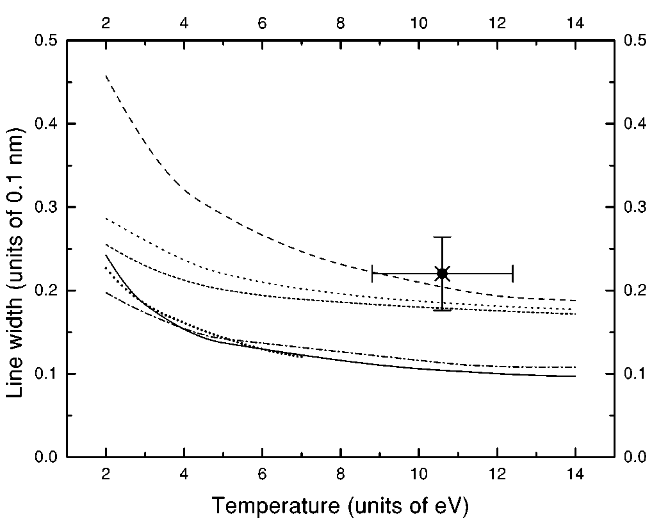

FIG. 4. Stark widths for the B III $2s$-$2p$ transition vs electron temperature for $N_e=1.8\times10^{18}$ cm^{-3}. Experimental value from Ref. [2]; theory: present work —, semiempirical (Ref. [1]) $\cdots$, semiempirical (Ref. [3]) ---, semiclassical (Ref. [4]) — — —, semiclassical (Ref. [5]) $\times$, R matrix (Ref. [6]) -·-, modified semiempirical (Ref. [23]) •••.

Having confirmed the results of the quantum calculations of Seaton [6], a first question is why impact-parameter, semiclassical [4,5] and closely related semiempirical [1,3] methods lead to substantially larger widths (closer to the experiment). The answer is related to the dominant role of collisions corresponding to total angular momentum quantum numbers $L_T\leq 4$ (see Sec. II) of the (colliding) electron-ion system. This fact is equivalent to saying that the spread of wave packets constructed in order to represent the colliding electrons classically is comparable to or larger than relevant impact parameters. (The ratio of de Broglie wavelength λ and impact parameter ρ is $\lambda/\rho=2\pi\hbar/m\rho v=2\pi/L$.) The wave packet spread leads to a reduction of the electron-ion interaction and thus to a decrease in the ensuing linewidth. This occurs because the electric fields causing Stark broadening are generated by local deviations from plasma charge neutrality, and because these deviations are reduced over spatial scales of the order of the de Broglie wavelength. Note also that even the most recent semiclassical calculations [24] explicitly account only for long-range dipole ($\Lambda=1$, $\propto r^{-2}$) and quadrupole ($\Lambda=2$, $\propto r^{-3}$) perturbations, although for collisions within the perturbed-electron radius there is also the short-range monopole $\Lambda=0$ term which, for example, has asymptotic matrix elements $\propto e^{-\gamma r}$ for S-S transitions [25]. This term is properly allowed for in the quantum calculations, and further smoothes the electron-ion interactions.

To illustrate the relation between relevant electron-ion separations at the perihelion r_{min} of the classical (unperturbed) orbits and angular momentum L corresponding to the impact parameter ρ, consider

$$\frac{r_{min}}{a_0}=\frac{1}{2}\frac{L^2}{\left[1+\left(\frac{L}{\eta}\right)^2\right]^{1/2}+1}, \tag{6}$$

which follows from Eqs. (116), (117), and (118) of Ref. [1] with the Coulomb parameter

$$\eta=\frac{2e^2}{\hbar v} \tag{7}$$

for doubly charged ions and electrons of velocity v. Our calculations with the Hartree-Fock code of Cowan [26] show that, for B III ions in the $2s$ and $2p$ states, the corresponding bound state mean radii are close to $1.6a_0$, while typical Coulomb parameters range from about 2 to 4 (for $E_e=10$ eV, $\eta\approx 2.3$). As can be seen from Table II, the classical orbits indeed penetrate deeply, or, at least, come to within factor 2 of the bound state orbits for angular momenta found to be most important in the quantum scattering calculations (see Fig. 3).

TABLE II. Ratio of the electron-ion perihelion to the Bohr radius for various values of angular momentum L and the Coulomb parameter η defined in Eq. (7).

L \ η	2	3	4
1	0.24	0.24	0.25
2	0.83	0.91	0.94
3	1.61	1.86	2.00
4	2.47	3.00	3.31

The theoretical conclusion that semiclassical calculations overestimate the electron collisional broadening of the B III $2s$-$2p$ lines by a factor of about 2 leaves one with the dilemma of having about the same disagreement with the experiment [2], for which the combined error in Stark width and electron density measurements was estimated to about 20%. A natural suggestion is to reconsider any possible systematic errors, a probable cause for such errors being hydrodynamic turbulence associated with plasma flows in the gas-liner, Z-pinch experiment [2], similar to the magnetohydrodynamical turbulence invoked [27,28] for interpretations of high-power Z-pinch experiments. This would be analogous to a more extreme situation encountered in the measurement of C V $1s2s$-$1s2p$ lines [29], which had also been found to be substantially broader than predicted theoretically. However, in this theoretically rather similar case of $\Delta n = 0$ transitions of He-like ions, there are both singlet and triplet lines, at rather different wavelengths of $\lambda = 3526$ Å or 2271 and 2277 Å, respectively. The measured widths were proportional to λ rather than λ^2, indicating Doppler rather than Stark broadening to dominate. Since these widths were larger than expected from thermal Doppler broadening and from Doppler shifts associated with radial flows, hydrodynamic turbulence in the laser-produced plasma used was inferred from this excess broadening, with an effective temperature of 600 eV.

Although radial laser-blowoff and pinch implosion velocities are very similar in these experiments, both approaching 10^7 cm/s, there is, of course, an essential difference in that the B III measurements were made in a 50-ns interval shortly after maximum compression, while the C V measurements were taken while axial velocities were still about 3×10^7 cm/s. However, this distinction may not be very important, because any turbulence from high-Reynolds-number flows decays only on a time scale τ of $l/\Delta v$ [30], if l is a characteristic length and Δv a typical spatial difference of flow velocities. With $l \approx 1$ cm and $\Delta v \approx 10^6$ cm/s, one would thus expect $\tau \approx 1$ μ sec, much too long for any turbulence to decay before the B III measurement interval.

As to typical Reynolds numbers

$$R = \frac{vl}{\nu} \tag{8}$$

during the pinch implosion, we estimate $R \approx 1.5 \times 10^4$ for $v = 5 \times 10^6$ cm/s, $l = 3$ cm, and a kinematic viscosity [31]

$$\nu = \frac{3 \times 0.96 T^{5/2}}{4e^4(\pi m_i)^{1/2} N_e \ln\Lambda}, \tag{9}$$

of 990 cm^2/s, at $T = 10$ eV, $N_e = 10^{18}$ cm^{-3}, and a Coulomb logarithm [31] of 6.1. Since the implosion takes more than 1 μs, developed and saturated turbulence therefore seems unavoidable, R being larger than critical Reynolds numbers [30]. Note also that any magnetic field effects are not likely to reduce the turbulence significantly, both because fields and plasma are probably fairly well separated [32] and because the corresponding parameter $\omega_{ci}\tau_i$ is well below 1 in any case (here ω_{ci} is the ion gyrofrequency and τ_i is the ion-ion collision time). Another question is the extent to which the turbulence is transported radially inward or mixed into the test gas region. However, even local Reynolds numbers are probably above critical over most of this region, and significant Reynolds stresses would be needed to compensate for the reduction in particle pressure implied below.

The reader may wonder whether the (collective) Thomson scattering diagnostics [33,34] used in the B III experiment [2] would not have indicated the existence of hydrodynamic turbulence. For sufficiently high concentrations of heavier elements in the hydrogen fill gas, the so-called impurity peak would then indeed indicate a higher temperature for these ions than for protons (see, e.g., Fig. 6 of Ref. [33]), although the larger width of this peak near peak compression could just as well be caused by turbulent velocities close to the thermal velocities of the protons provided the turbulent eddies are smaller than the scattering volume. For relatively high impurity concentrations, radiative energy losses are very important [35], facilitating a more rapid decay of the turbulence than estimated above. This is consistent with the narrower impurity peaks at later times (see Fig. 5 of Ref. [33]), whose widths are consistent with thermal Doppler broadening at equal temperatures for the various ions.

The B III experiment, on the other hand, was done with very small concentrations of BF_3 to avoid self-absorption of the $2s$-$2p$ lines. The impurity feature on the scattering spectrum could therefore not be observed [36], and at the same time the dissipation of the turbulent energy would have taken much longer, say, the 1-μs plasma lifetime quoted in Ref. [2]. One is therefore left with the possibility of an alternative interpretation of the scattering spectra, e.g., of that shown in Fig. 2 of Ref. [36]. That is, instead of inferring a temperature of 10 eV, essentially from the width of the proton feature, assume turbulent rms velocities equal to proton thermal velocities. This also means lower temperatures for the protons, say, 5 eV. As emphasized by Glenzer and Kunze [2], electron-ion relaxation times are extremely short, so that we also infer $T_e \approx 5$ eV. This is a much more favorable electron temperature for the observation of the B III $2s$-$2p$ lines than 10 eV in this nearly steady state plasma, because at 5 eV about 20% of the boron ions are B III, contrasted to less than 1% at 10 eV. Independent evidence for $T_e \lesssim 5$ eV could be provided by the absence of the $3d$-$4f$ line at 2077 Å, reported in Ref. [2], whose intensity was evidently $\lesssim 5\%$ of the 2066-Å line. At 10 eV, the relative intensity of the 2077-Å line would be about 1. (Note that standard local thermodynamic equilibrium relations can be used for this estimate, to within about 10% for the temperature. Since the $3d$-$4f$ line may be about 3 Å wide, corresponding line ratio measurements would best be done at reduced spectral resolution.) Any deviations between shapes of thermal and thermal plus turbulence scattering spectra would probably be too small to be observable, leaving its width as the major invariant. Some deviations could, of course, be indications of non-Gaussian distributions of the turbulent velocity components.

Besides suggesting investigations of turbulence in the gas-liner pinch, perhaps along the lines of Ref. [34] and by use of line pairs with different sensitivities to Stark and Doppler broadening [29], it remains to be shown that the level of turbulence assumed here would suffice to obtain agreement of measured linewidths with quantum-mechanical calculations. Note first that there will be no significant change in the electron density, $N_e = 1.8\times10^{18}$ cm^{-3}, because of the large value of the scattering parameter α, i.e., of $(k\lambda_D)^{-1}$, k here being the wave number of the electron density fluctuation responsible for the scattering, and λ_D the Debye length [33]. However, the predicted electron-collisional width of, e.g., Ref. [6], is now 0.14 Å because of the reduced electron temperature, whereas the predicted total Doppler width is increased by a factor $(11.8/2)^{1/2}$ to 0.125 Å, $11.8 = 10.8 + 1$ standing for turbulent plus thermal Doppler broadening at a boron-proton mass ratio of 10.8, 1/2 for the reduction in temperature. With 0.07- and 0.05-Å Lorentzian and Gaussian instrumental broadening [36], and 0.02-Å proton impact broadening [4], this gives a total linewidth [37,38] of 0.28 Å, i.e., more than 90% of the measured total width [2]. There would therefore be agreement well within combined experimental and theoretical errors relative to the previous quantum-mechanical calculations and, more marginally, also with the present calculations, which result in 0.27 Å, if one allows again for a 0.02 Å contribution from ion-ion collisions, were the degree of turbulence indeed as high as assumed here. Verification of this assumption would remove a major obstacle in our quantitative understanding of Stark broadening of isolated lines from multiply ionized atoms, including possibly the anomalous scaling of linewidths along isoelectronic sequences [39–42]. In the last experiment, on $2s3s$-$2s3p$ linewidths of Be-like Neon, improved semiclassical calculations [24] were found to be consistent with the measured widths, but judging from the present B III $2s$-$2p$ comparisons and given similar ratios of impact parameters and bound state radii, this agreement may again be spurious.

IV. CONCLUSIONS

A fully quantum-mechanical calculation of the Stark linewidth for the $2s$-$2p$ line of B III was carried out with the use of the latest atomic data reflecting the present state-of-the-art in atomic collision theory. Although the obtained results agree well with the previous quantum R-matrix Stark widths, the difference with semiclassical and some semiempirical calculations, as well as with the measured values, is of order of 2. This seems to originate in (i) failure of the nonquantum calculations for small impact parameters which are most important for the linewidth in question, and from (ii) not accounting for the turbulent plasma motion which significantly affects the determination of Doppler broadening and plasma temperature. Independent ion linewidth measurements for plasmas with well-known parameters, not subject to significant contributions from other line broadening mechanisms than Stark broadening, continue to be very important.

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