

Plasma screening effects in Stark broadening: A fully relativistic close-coupling approach

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Stark broadening of spectral lines in plasmas is a cornerstone of opacity modeling and plasma diagnostics, with critical implications for controlled fusion and astrophysics. Despite recent advances in fully quantum-mechanical close-coupling calculations for electron-impact broadening, the impact of denser plasma environments remains largely unexplored due to theoretical bottlenecks associated with electron-ion collision processes. Based on our close-coupling theory for electron-ion collisions in plasmas, which resolves the problem of extracting short-range scattering phase shifts, we introduce a fully relativistic close-coupling approach for the Stark broadening that incorporates plasma screening effects. Systematic investigations of hydrogenic radiators reveal distinct patterns of line broadening dependence on plasma conditions, offering valuable insights for plasma diagnostic applications. Furthermore, we provide a quantum-mechanical interpretation of the screening factor commonly introduced in semiclassical impact theories. This work establishes a robust foundation for future studies on complex atomic systems in high-density plasmas.

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I. INTRODUCTION

Stark broadening is the pressure broadening of the spectral lines of a radiating atom (ion) caused by charged particles in the surrounding plasma [1]. It provides an essential input for opacity modeling [2]. Moreover, an accurate understanding of Stark broadening is crucial for the spectroscopic diagnostics of laboratory and astrophysical plasmas [3]. Therefore, it has extensive applications in astrophysics, controlled fusion, and high-energy-density physics research [4]. Previous experimental and theoretical studies have mostly focused on low-density plasmas [5]. Extending the theory of impact broadening of spectral lines to denser plasma environments is of great significance for both fundamental research and related applied studies.

Spectral lines from atoms and ions embedded in plasmas are shaped not only by the individual atomic properties of the radiator but also by the statistical influence of the surrounding plasma environment. Theoretical description of Stark broadening is therefore very challenging, as it lies at the interface of atomic physics, plasma physics, and statistical physics [6,7]. Although the theoretical framework for a unified treatment of ions and electrons in Stark broadening has been proposed

based on the large-scale molecular dynamics simulations [8] as well as Green's function approaches [7,9], the large number of physical ingredients involved makes such a comprehensive description impractical for most applications. Consequently, due to the large mass difference between ions and electrons, most theoretical investigations of Stark broadening consider the contributions from ions and electrons separately according to the ratio between the characteristic collision velocity v and impact parameter b [1].

Ion perturbors move slowly and typically interact with radiators at relatively large distances, so that the ratio v/b is small. As a consequence, the electric field produced by the ions varies only weakly over the radiative timescale of the transition. Under these conditions, many ions can substantially influence a radiator simultaneously, and a single binary-collision picture is not appropriate. This physical situation justifies the quasistatic approximation, in which the atomic response is described by the Stark effect in an external field whose instantaneous value is determined by the collective contribution of many ions, thereby giving rise to a statistical description of the plasma microfield. The pioneering work of Holtsmark established the foundation for this approach, which remains a cornerstone of ion broadening theory [10,11].

Electrons, in contrast to ions, are fast and highly penetrating perturbors. Their interactions with radiators are dominated by close encounters involving small impact parameters, so the ratio v/b is large. The electron contribution is usually much larger than the ion contribution [1]. There are three primary methods for describing the electron contribution to Stark broadening, i.e., the impact theory [12–16], the relaxation

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theory [6,17–19], and the kinetic theory [20]. The general forms of the line shape expressions from these three theories are the same, with the differences entering mainly through the specific form of the electron-impact broadening operator [1]. Although the relaxation theory and the kinetic theory are mathematically more rigorous and provide statistical descriptions of electron-impact broadening by accounting for the cumulative effect of many electron collisions on the radiating states, many approximations involved in the impact theory also have to be made for their practical use, such as the binary collision assumption [18]. In this framework, line broadening arises from a sequence of short-lived, well-separated binary collisions, and the effect of an individual collision is characterized by a scattering matrix connecting the radiator states before and after the encounter. Averaging over many independent collisions then yields an electron-impact broadening operator that determines the spectral width and shift. Therefore, the key physical quantity for electron broadening is the modeling of scattering processes, which are closely related to electron-atom (ion) collision theory, as recognized in early works by Regemorter [21] and Sahal-Br           [22].

The treatments of the scattering processes for electron-radiator collisions can be broadly divided into two categories. When the plasma density is low, the collision can be treated as a weak, short-duration perturbation, and one can use the semiclassical approaches, which are computationally efficient and have been widely used in practical Stark broadening calculations [1,22–24]. In these approaches, the internal structure of the radiator is treated quantum mechanically, while the perturbing electron is assumed to move along a classical trajectory, typically approximated as a straight line or hyperbolic path. On the other hand, as the plasma density increases, close encounters induce strong short-range interactions, and the probability of electron penetration into the inner atomic region drastically increases, where a full quantum-mechanical description of both the electron and the radiator within a unified scattering framework is required [12–14,25–30]. There are two common approximations for the quantum scattering processes: perturbative first-order Born/distorted-wave or second-order approximation for the electron-impact broadening operator [1,25,26] and the dipole approximation for the Coulomb interaction between atoms and plasma particles [1]. Only very recently have full-order close-coupling scattering calculations without the dipole approximation been developed [11,17,18,27–30], and the importance of resonances in electron collisions has been demonstrated [27,29,30].

In denser plasma environments, the increased probability of electron penetration necessitates not only fully quantum-mechanical scattering calculations but also a fully relativistic treatment. In addition, many-body collision effects are expected to become significant, among which the collective screening effect is the most prominent, where the collective response strongly modifies interparticle interactions. As a result, individual charged particles no longer interact through the bare Coulomb potential, but rather through an effective interaction screened by the surrounding plasma, thereby affecting the energy-level structure and dynamical processes [31–36]. For electron-collision processes, particle interactions in plasmas are commonly described using screened potentials, such as the Debye-H           potential [37]

or atomic-state-dependent effective potentials [38], which represent the statistical averaging of the collective effects from the surrounding plasma’s ion interactions. Most existing quantum-mechanical calculations [25–30] are performed for isolated atoms (ions) and do not systematically incorporate plasma screening, not only because of the scarcity of experimental data on line broadening in dense plasmas, but also due to intrinsic difficulties in collision theory, particularly for ionic systems. Because screening alters the long-range Coulomb boundary conditions, it complicates the accurate extraction of screened short-range scattering phase shifts, making it difficult to obtain reliable scattering matrices for Stark broadening calculations. It should be noted that in some semiclassical treatments, screening is introduced through a cutoff, typically to truncate the range of the Coulomb interaction (or, equivalently, the maximum impact parameter) for avoiding the divergence of classical-trajectory integrals, while its detailed physical picture has yet to be clarified [1].

Recently, we have developed a fully relativistic close-coupling theoretical approach for electron-impact broadening, which solves the multichannel scattering problem without invoking a weak-interaction assumption [27–30]. This approach provides a nonperturbative description of the collision dynamics, allowing close encounters, channel coupling, exchange effects, and resonance structures to be treated consistently. Although computationally more demanding, such approaches offer a more complete and systematic description of electron-radiator collisions, particularly in regimes dominated by low-energy electrons and strong interactions. We have also developed a close-coupling theory that incorporates plasma screening by means of an *R*-matrix method for determining scattering matrices under screened interaction potentials [39].

II. THEORETICAL METHOD

A. Stark line profiles

In this work, we further extend our previous electron-impact broadening code [29,30] to include contributions from both ions and electrons. The line profile is obtained by averaging over the ionic microfield distribution, while electron collisions enter through the electron-impact broadening operator ϕ . The Stark line profile of one-electron systems is given by [1,11]

$$L(\Delta\omega) = -\left(\frac{1}{\pi}\right) \text{Re} \text{Tr} \int_0^\infty dF W(F) \times \{\Delta_d[i\Delta\omega - iCF + \phi]^{-1}\}, \quad (1)$$

where $\Delta\omega$ is the frequency separation from the unperturbed line, Δ_d is the dipole operator, $W(F)$ is the Griem-Holtmark microfield distribution [1], and C is the linear Stark coefficient [1],

$$C = \frac{3}{2} n(n_1 - n_2) \frac{ea_0}{\hbar Z}, \quad (2)$$

where n_1, n_2 are parabolic quantum numbers. The iCF term corresponds to the ion contribution. The real and imaginary parts of ϕ correspond to the electron-impact width w and shift d , respectively, which are evaluated using the effective collision strengths obtained from quantum scattering calculations

as [25,26]

$$\phi = w + id = 2N_e \left(\frac{\hbar}{m_e} \right)^2 \left(\frac{2m_e \pi}{k_B T_e} \right)^{1/2} \times \int_0^\infty \Gamma(\varepsilon) \times \exp\left(\frac{-\varepsilon}{k_B T_e} \right) d\left(\frac{\varepsilon}{k_B T_e} \right). \quad (3)$$

$$\Gamma = \sum_{J_i^T J_f^T j j' l l'} (-1)^{J_i + J_f + 2J_f^T + j + j'} \frac{1}{2} (2J_i^T + 1) (2J_f^T + 1) \times \begin{Bmatrix} J_f^T & J_i^T & 1 \\ J_i & J_f & j \end{Bmatrix} \begin{Bmatrix} J_f^T & J_i^T & 1 \\ J_f' & J_i' & j' \end{Bmatrix} \\ \times [S_{ll'} \delta_{jj'} \delta_{J_i J_i'} \delta_{J_f J_f'} - (S_l(J_i' l' j' J_i^T; J_i l j J_i^T) \times S_F^*(J_f' l' j' J_f^T; J_f l j J_f^T))], \quad (4)$$

where S_l and S_F are the scattering matrices of the upper and lower states, respectively, and they are calculated under the same incident electron energy ε of colliding electrons.

B. Relativistic R -matrix determination of screened scattering matrices

To incorporate plasma screening, we replace the electron-ion as well as electron-electron Coulomb interactions with Debye-screened potentials in the electron scattering calculations. More specifically, the electron-atom (ion) scattering problem is treated using a fully relativistic close-coupling R -matrix method, in which the complete electron-electron interaction is included without invoking the dipole approximation, following the formulation developed in Ref. [39]. The long-range polarization effects in the outer region are treated rigorously, without adopting the approximations commonly employed in earlier works [40]. Within this framework, the screened short-range scattering matrix is determined by matching the asymptotic boundary condition with the R -matrix $R_{i'j'}$ at the matching point r_a , i.e.,

$$F_{ij}(r_a) = \sum_{i'} R_{i'j'} \left[r_a \frac{dF_{i'j'}(r)}{dr} - b F_{i'j'}(r) \right]_{r=r_a}, \quad (5)$$

with F_{ij} and $dF_{ij}(r)/dr$ the channel radial wavefunction and its derivative, respectively. b is a constant parameter in the R -matrix definition, which is usually zero. At large distances, where the potential is dominated by the centrifugal term, F_{ij} can be expressed as

$$F_{ij}(r) = S_i(kr) \delta_{ij} + C_i(kr) K_{ij}, \quad (6)$$

where K_{ij} is the scattering K matrix and the scattering S matrix in Eq. (4) is calculated by the definition $S = (1 - iK)^{-1} (1 + iK)$. Unlike the usual electron-atom scattering calculations, where $S_i(kr)$ and $C_i(kr)$ are the regular and irregular Riccati-Bessel functions (or Coulomb wavefunctions for ion target), respectively, the most crucial step here is to use numerically calculated regular and irregular scattering wavefunctions $S_i(kr)$ and $C_i(kr)$ of the screened Coulomb potential, which have a phase difference of $\pi/2$. In Ref. [39], we have developed a numerical algorithm for this purpose, which was also adopted in the present work. In this way, we can extract a well-defined short-range scattering matrix, which is independent of the choice of asymptotic matching point r_a .

Here, T_e , N_e , and ε denote the electron temperature, electron density, and incident electron energy, respectively. The effective collision strength Γ is obtained from the scattering matrices connecting the initial and final states of the radiative transition [29,30]:

It should be emphasized that the effective Γ defined in Eq. (4) differs fundamentally from the conventional collision strengths or scattering cross sections commonly used in electron-atom collision calculations. In conventional scattering calculations, the relevant quantities are inelastic cross sections from the specific ground or excited states. In this case, as the inelastic processes happen in a region close to the target, the short-range scattering phase shifts are insensitive to the choice of $S_i(kr)$ and $C_i(kr)$ in the asymptotic region. Therefore, previous distorted-wave calculations using the pure Coulomb wavefunctions could give reasonable results [36,41–43]. On the other hand, for the present electron-impact broadening calculations, the effective Γ is related to the total collision cross sections for excited atoms or ions. Therefore, by using the unitary property of the scattering matrix, the scattering matrices S_l and S_F in Eq. (4) are closely related to the elastic collision processes, which are very sensitive to the choice of $S_i(kr)$ and $C_i(kr)$. Only the physically correct choice of the asymptotic wavefunctions can yield a well-defined short-range scattering matrix, which is independent of the matching point, especially for the ion target.

III. RESULTS AND DISCUSSION

Figure 1(a) shows Γ for the hydrogen $3d^+ - 2p^+$ component at several Debye screening lengths. As the screening becomes stronger (smaller D), Γ decreases systematically over most of the incident energy range. An exception is observed at $D = 30$ a.u., where Γ rises noticeably relative to the $D = 50$ a.u. case in the low-energy region. Under weak screening ($D = 200$ a.u.), a comparison of Γ results with (solid line) and without (dotted line) the polarization effect demonstrates that this effect enhances Γ in the low-energy region. In contrast, under strong screening ($D = 30$ a.u.), the near overlap of results with (solid line) and without (dotted line) the polarization effect across the entire energy range indicates that the long-range polarization contribution is significantly suppressed. This observation contrasts with the expected prominent effect under weaker screening, directly demonstrating the suppression mechanism as screening intensifies. Figure 1(b) presents the corresponding Γ for the $3d^+ - 2p^+$ transition of He^+ . With increasing screening, the resonance structures associated with higher Rydberg series are progressively damped, while resonances from lower series shift to higher energies; meanwhile, the overall magnitude of Γ also decreases as screening

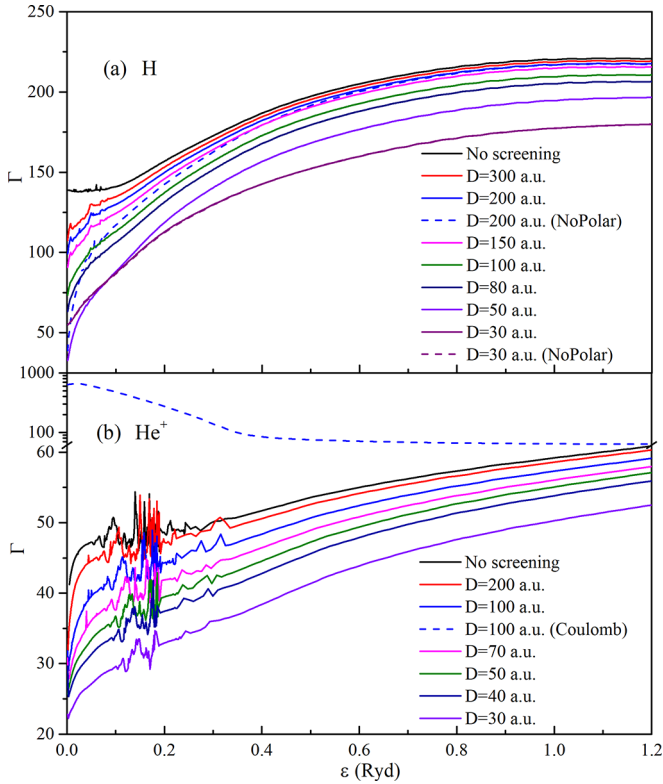


FIG. 1. Screening suppresses low-energy collision strengths Γ for the $3d^+-2p^+$ transition in H [panel (a)] and He^+ [panel (b)].

strengthens. In contrast, the Γ values (dotted line) obtained when the short-range scattering matrix is extracted using unscreened asymptotic Coulomb wavefunctions are noticeably larger than those from all properly screened treatments, highlighting the crucial role of short-range scattering matrix extraction. Such an approach, commonly adopted in earlier distorted-wave theories [36,41–43], can lead to unphysical Stark widths in high-density plasma conditions.

Relativistic quantum-mechanical calculations naturally give rise to fine-structure splittings of atomic levels. Under experimental conditions, however, the individual fine-structure components strongly overlap and are observed as a single spectral feature. Throughout this work, the reported Stark widths therefore correspond to oscillator-strength-weighted averages over all fine-structure components of a given transition [28]. To verify the correctness of our code, Figs. 2 and 3 present benchmark comparisons under low-density plasma conditions. In Fig. 2, our calculated shifts of the H_β line are compared with the experimental measurements of Wiese *et al.* [44], as well as with results from relaxation theory [18] and kinetic theory [18]. The present results show good agreement with the measured values. In comparison, the shifts predicted by kinetic theory are several times larger than those obtained in the present calculations, possibly due to the limitations of the approximations employed in the specific calculations, as discussed in Ref. [18]. In contrast, the relaxation theory results are in close agreement with our values.

In Fig. 3, our calculated Ly_α line profiles are compared with representative results from existing theoretical approaches, including semiclassical Vidal-Cooper-Smith (VCS)

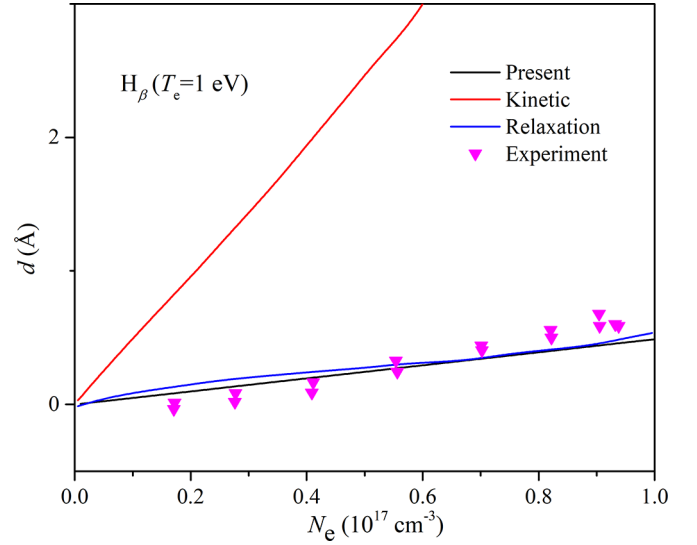


FIG. 2. Comparison of calculated H_β line shift obtained from different theoretical models [18] and measured values [44].

model [17], classical particle simulations [45], and fully quantum-mechanical calculations [17]. Overall, our quantum-mechanical results are consistent with these established calculations, confirming the reliability of the present approach.

Figures 4 and 5 examine the dependence of the H_α Stark width on electron density for neutral hydrogen and singly ionized helium, focusing on high-density regimes where plasma screening becomes significant. Figure 4 compares our calculated H_α widths for hydrogen with high-density experimental measurements by John and Nicole [46], which constitute a stringent benchmark. Semiclassical results by Griem [1] and Vidal *et al.* [47] are also shown for comparison. Three quantum-mechanical calculations are presented: an isolated calculation with polarization (blue), a screened calculation without polarization (red), and a screened cal-

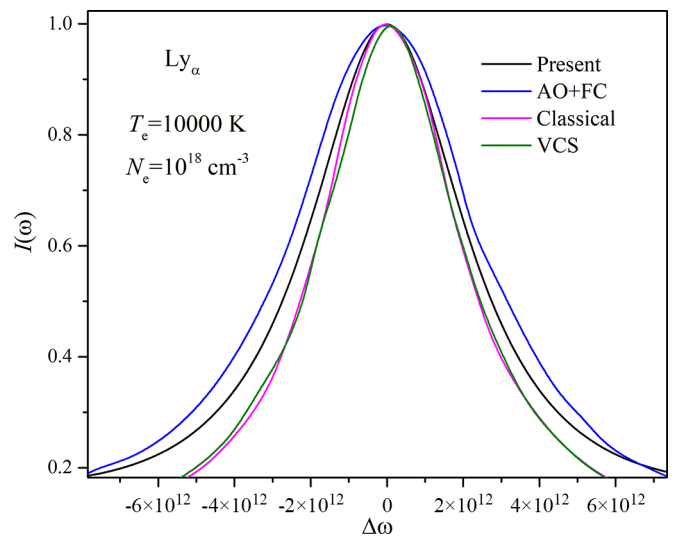


FIG. 3. Comparison of calculated Ly_α line profiles obtained from different theoretical models [17,45].

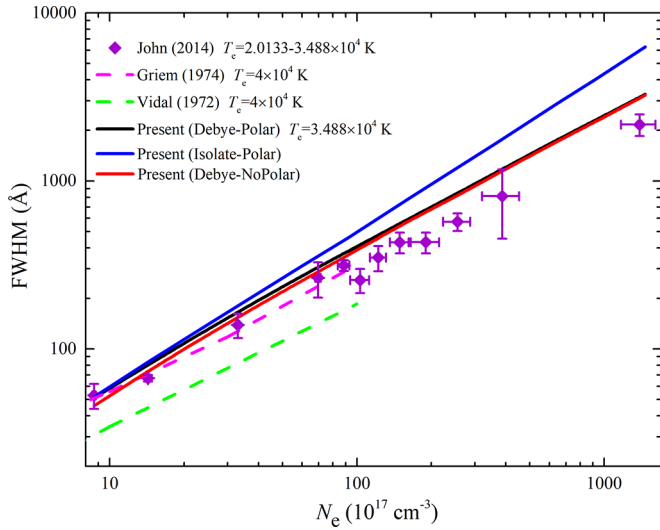


FIG. 4. Comparison of Stark broadening of the H_α line of H, semiclassical results from Griem [1] and Vidal *et al.* [47], and experimental data from John and Nicole [46].

culation with polarization (black). For the isolated case, as electron density increases, discrepancies between theory and experiment become more pronounced. At the highest measured density ($N_e = 1.39 \times 10^{20} \text{ cm}^{-3}$), the isolated result overestimates the experimental width by a factor of 2.79. Plasma screening substantially reduces the linewidth, whereas the long-range polarization effect is significant only at low densities. At the lowest electron density considered ($N_e = 8.63 \times 10^{17} \text{ cm}^{-3}$), the influence of screening can be ignored, whereas polarization increases the width by about 12%. As the density increases, the polarization effect is progressively suppressed and becomes insignificant. In contrast, including screening reduces the linewidth by up to 48% at densities around 10^{20} cm^{-3} , leading to markedly improved agreement with experiment. At this highest density point, the

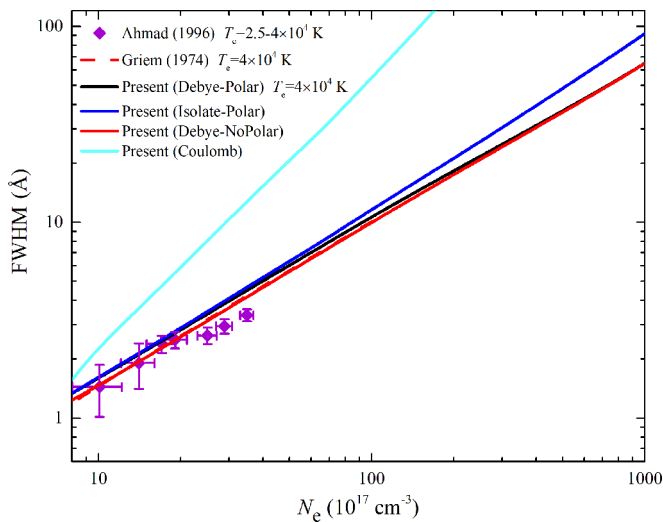


FIG. 5. Comparison of Stark broadening of the H_α line of He^+ , semiclassical results from Griem [1], and experimental data from Ahmad [48].

theory-to-experiment ratio drops to 1.44, and the average ratio across the studied density range is 1.33. The difference between the results of Vidal *et al.* [47] and the experiment is significant, whereas Griem's calculations [1] reproduce the experimental density dependence well in the low-density region. However, the two semiclassical models exhibit trends that differ markedly from our results, raising questions about the reliability of their extrapolation to high-density plasma conditions.

Figure 5 presents corresponding results for the H_α Stark widths of He^+ . Besides the isolated and screened results (without/with polarization), a fourth calculation is also shown for comparison (cyan), where scattering phase shifts are extracted using Coulomb wavefunctions as asymptotic solutions in a screened plasma. In Debye plasmas, the use of unscreened Coulomb asymptotic functions yields systematically larger electron-impact widths than properly screened calculations, demonstrating that such treatments overestimate the widths. This indicates that accurate extraction of screened short-range polarization phase shifts is essential for Stark width calculations of ionized radiators in plasmas. For He^+ , the experimental densities [48] are relatively low. Consequently, over this measured range, the screened and isolated calculations remain close, with plasma screening exerting only a modest influence. The long-range polarization interaction affects the widths mainly at low densities; at the lowest density considered ($N_e = 8 \times 10^{17} \text{ cm}^{-3}$), where it increases the Stark width by about 8.5%. At the highest density ($N_e = 1 \times 10^{20} \text{ cm}^{-3}$), however, screening reduces the width by about 30%. Our screened results agree well with the measurements, giving an average theory-to-experiment ratio of 1.23. In addition, our screened results are also in good agreement with Griem's calculations [1]. The close agreement in both magnitude and trend between the semiclassical results and the screened calculations indicates that the short-range scattering matrix obtained from Eq. (6) provides the quantum-mechanical physical picture of the screening factor used in semiclassical theories; i.e., the screened short-range scattering processes are the key processes for electron-impact broadening.

Figure 6 examines the dependence of the H_α Stark width on electron temperature for neutral hydrogen and singly ionized helium. For the isolated case, the Stark width increases monotonically as T_e decreases. When plasma screening is included, this temperature dependence is substantially weakened. For H [Fig. 6(a)], the Stark width becomes nearly insensitive to T_e at high electron densities and even shows a slight decrease on the lower T_e side of the explored range. At $N_e = 1 \times 10^{19} \text{ cm}^{-3}$, the turnover appears below $T_e \approx 2.5 \times 10^4 \text{ K}$, whereas at $N_e = 1 \times 10^{20} \text{ cm}^{-3}$, a similar behavior sets in at $T_e \approx 12.5 \times 10^4 \text{ K}$. A similar behavior is observed for He^+ [Fig. 6(b)]. At $N_e = 1 \times 10^{20} \text{ cm}^{-3}$, the Stark width shows a clear nonmonotonic temperature dependence, with the turnover occurring around $T_e \approx 7.5 \times 10^4 \text{ K}$.

Considering that Griem's semiclassical dataset [1] is limited, a simple extrapolation based on its trend yields a similar nonmonotonic behavior, but somewhat qualitatively different temperature dependences. Although Griem's semiclassical results in the relatively low temperature regions compare well with our calculations, these different temperature behaviors indicate the importance of fully quantum-mechanical treat-

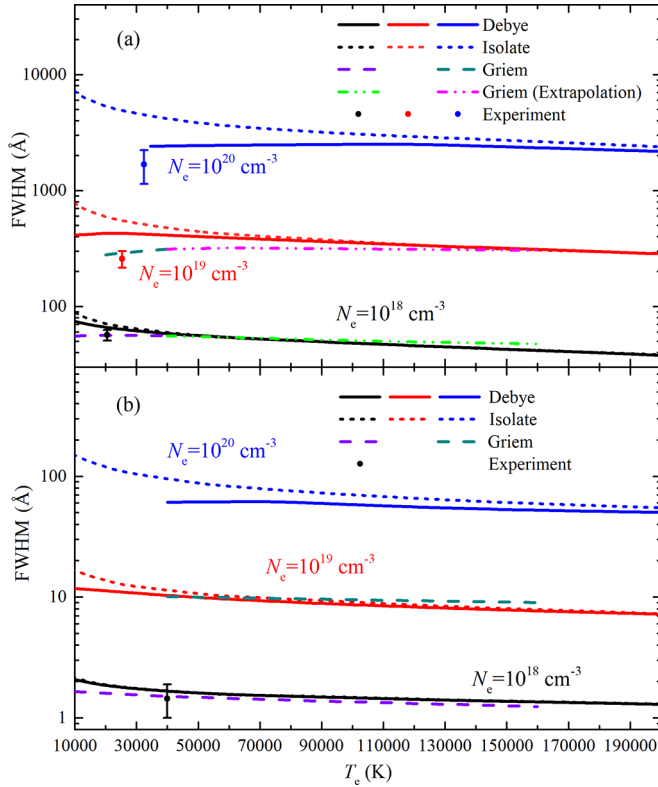


FIG. 6. Comparison of Stark broadening of the H_α line of H [panel (a)] and He^+ [panel (b)], semiclassical results from Griem [1]. The circles with error bars represent experimental data from John and Nicole [46] for H and Ahmad [48] for He^+ .

ments over extended temperature and density regions. Experimental data on the temperature dependence of the H_α Stark width are very limited, which are unavailable for our plasma conditions. To facilitate comparison with our calculations, we have replotted the experimental data at one temperature from Refs. [46,48] in Fig. 6. For H at $N_e = 1 \times 10^{19} \text{ cm}^{-3}$ and He^+ at $N_e = 1 \times 10^{18} \text{ cm}^{-3}$, the experimental data points align almost exactly with the target density. For H at $N_e = 1 \times 10^{18} \text{ cm}^{-3}$ and $N_e = 1 \times 10^{20} \text{ cm}^{-3}$, the data points were derived via log-log linear interpolation using the two nearest neighboring experimental values. More experimental work on systematic temperature variations is highly desirable.

Under the same plasma conditions, the screening-induced changes in He^+ widths are smaller than those in H, reflecting the stronger Coulomb attraction in ionized radiators that partially offsets the screening of the electron-radiator interaction. These results indicate that while H_α width provides a viable density diagnostic in high-density plasmas, its effectiveness for temperature diagnostics is reduced due to a significantly weakened width-temperature dependence.

IV. CONCLUSION

In summary, by incorporating plasma screening directly at the level of electron-radiator scattering, we have established a quantum-mechanical framework for treating plasma-screening effects on Stark broadening in dense plasmas and applied it to hydrogenic lines. The resulting Stark widths exhibit significantly improved agreement with available experimental measurements at high electron densities. Our results demonstrate that plasma screening plays a key role in electron-impact broadening at high electron densities. In particular, for ionized radiators, we show that a proper treatment of screened boundary conditions is essential, as the use of unscreened Coulomb asymptotics leads to systematic overestimation of Stark widths. Comparisons with semiclassical theories indicate that short-range scattering phase shifts provide a quantum-mechanical physical picture for the screening factor used therein. The screening-induced suppression of low-energy collision strengths leads to a modified density dependence and, in some cases, a nonmonotonic temperature dependence of the H_α width. This implies that H_α Stark broadening remains a robust diagnostic of electron density, whereas its sensitivity to temperature is significantly reduced in dense plasmas due to the screening-induced suppression of the width-temperature dependence. Although plasma screening is treated here within the Debye potential, this framework is readily applicable to general multielectron atomic systems. The present calculations provide a quantum-mechanical reference for assessing screening effects on Stark broadening. Extensions to more refined effective interaction models [38] and ionic microfield distributions beyond the present Griem-Holtmark treatment, as well as applications to other ionic radiators, are left for future work. In addition, further high-density experimental measurements would be particularly valuable for benchmarking plasma-screening effects.

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

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