Influence of many-particle effects on spectral line shapes in nonthermal plasmas

S. Günter and A. Könies
Fachbereich Physik, Universität Rostock, Universitätsplatz 3, 18051 Rostock, Germany
(Received 19 October 1993)

A many-particle theory is applied to investigate the influence of plasma oscillations on spectral line profiles. Collective plasma modes in equilibrium plasmas are known to influence only the line shift, not the shape of spectral lines. In nonequilibrium plasmas, however, the frequency-dependent width of the line becomes resonant near the electron plasma frequency. Dips on the profile resulting from these resonances could be found calculating the L_α line profile. Their position and shape excellently agree with experimental results.

PACS number(s): 52.25.Rv, 32.70.Jz

I. INTRODUCTION

Recently, structures on the profiles of spectral lines have been observed in some experiments for dense plasmas. Thus, "dips" on the hydrogen L_α profile have been found at electron densities of about 2×10^{18} cm^{-3} [1]. These measurements have been performed in a gas-liner pinch. Surprisingly, at a capillary discharge, a hydrogen H_α profile with large structures has been measured [2]. Remarkably, the structure's distance from the line center at both the L_α and the H_α lines is proportional to the square root of the electron density.

According to a developed theory [1,3–6], such structures are explained as being caused by a simultaneous interaction of the radiating atom with a static and a dynamic electric field. The static field has been identified with the quasistatic ionic microfield, whereas the electron plasma oscillations have been described by a quasimonochromatic field. In such a way, resonances on the line profile have been predicted. However, only the positions of resonances on the line profile could be calculated. No statements could be made about the magnitude of the structures on the profile and their extent in the detuning. Unfortunately, this is crucial to answering the question of the experimental visibility.

The aim of this paper is to calculate spectral line profiles including effects due to plasma oscillations. For an appropriate description of such collective effects, a many-particle theory has to be applied [7,8]. Here an earlier-developed many-particle approach based on a Green's-function technique will be used.

In the following, therefore, first the theory of frequency-dependent electronic widths and shifts of spectral lines including many-particle effects will be developed. The consideration of these widths and shifts should give the position as well as the magnitude of the structures on the line profile. In Sec. III the influence of plasma oscillations on the hydrogen L_α line profile will be studied for thermal plasmas. Finally, in Sec. IV the resonance effects in weakly nonthermal plasmas will be investigated. It will be shown that for nonthermal plasmas remarkable structures on the line profiles due to plasma oscillations can be obtained.

II. THEORY

In dense plasmas, collective effects become important and, e.g., plasma oscillations and dynamic screening play an important rule. Therefore, a many-particle theory should be applied to describe such plasma conditions.

In some preceding papers a many-particle approach based on a Green's-function technique was developed and has already been used to study collective plasma effects [7]. Up to now, the point of interest was the influence of dynamic screening effects on the shift of hydrogen lines at high electron densities [9]. It has been shown that in dense plasmas the line shift becomes nonlinear with respect to the electron density. Dynamic screening effects which become important if the distance of the radiators' energy levels is of the order of magnitude of the plasma frequency has been found to be the reason for this effect.

In this paper the influence of dynamic screening on the width of spectral lines will be investigated. Therefore, it is necessary to go beyond the well-known impact approximation and find a frequency-dependent width of spectral lines. This can easily be done in the frame of the developed theory [7]. Thus an electronic self-energy for each component depending on both the detuning $\Delta\omega$ and the normalized microfield strength β is obtained:

$$\langle i|\Sigma(\Delta\omega)|i\rangle = -\frac{1}{e^2}\int\frac{d\mathbf{q}}{(2\pi)^3}V(q)\int_{-\infty}^{+\infty}\frac{d\omega}{\pi}\mathrm{Im}\varepsilon^{-1}(\mathbf{q},\omega+i\delta)[1+n_B(\omega)]\sum_\alpha\frac{1}{E_i^0+\Delta\omega-E_\alpha(\beta)-(\omega+i\delta)}|M_{i\alpha}^{(0)}(\mathbf{q})|^2 . \tag{1}$$

Here, $n_B(\omega)$ is the Bose function, e is the elementary charge, $V(q)=4\pi/q^2$ is the Fourier transform of the Coulomb potential, and M is the isolated vertex function given in [7].

III. RESONANCE EFFECTS IN THERMAL PLASMAS

According to Eq. (1), the width of an atomic level is given by

$$w_i=\mathrm{Im}\langle i|\Sigma(\Delta\omega)|i\rangle=\frac{1}{e^2}\int\frac{d\mathbf{q}}{(2\pi)^3}V(q)\sum_{\alpha}|M_{i\alpha}^{(0)}(\mathbf{q})|^2[1+n_B(\omega)]\mathrm{Im}\varepsilon^{-1}(\mathbf{q},\omega+i\delta)\delta(E_i^0+\Delta\omega-E_\alpha(\beta)-\omega)\ . \tag{2}$$

As shown in [7], in Eqs. (1) and (2) many-particle effects are retained only in the inverse dielectric function $\epsilon^{-1}(\mathbf{q},\omega)$. In the following calculations, for the dielectric function the well-known random phase approximation

$$\epsilon(\mathbf{q},\omega)=1-V(q)\frac{n_e\sqrt{\pi}}{2q\sqrt{k_BT}}i\left\{w\left[\frac{1}{\sqrt{k_BT}}\left(\frac{q}{2}-\frac{\omega}{q}\right)\right]-\omega\left[\frac{1}{\sqrt{k_BT}}\left(-\frac{q}{2}-\frac{\omega}{q}\right)\right]\right\}, \tag{3}$$

with

$$w(x)=\mathrm{erfc}(-ix)\ , \tag{4}$$

will be used. In Eq. (3), n_e is the electron density, k_B is the Boltzmann constant, and T is the electron temperature.

Introducing the dielectric function into Eq. (2), it has to be considered at frequencies $\omega\approx E_i^0+\Delta\omega-E_\alpha(\beta)$. Therefore, resonances occur if

$$\omega\approx\omega_{\mathrm{pl}}=E_i^0+\Delta\omega-E_\alpha(\beta) \tag{5}$$

holds. Such resonances already have been found in [10,11]. As an example, Fig. 1 shows the imaginary part of the self-energy (electronic width) of the central L_α component of hydrogen. Whereas the dashed line corresponds to the electronic width without ionic microfield, the solid line has been calculated using an averaged ionic microfield ($\beta=E/E_0=1$, $E_0=e/4\pi\varepsilon_0r_0^2$, with $(4\pi/3)r_0^3=1/n_e$) has been chosen. The maxima result from the resonances at the plasma frequency and, therefore, their detuning form the line center is

$$\Delta\omega=\omega_{\mathrm{pl}}+E_\alpha(\beta)-E_i^0\ . \tag{6}$$

Calculating the width of the central L_α component, two virtual transitions have to be taken into account. Therefore, for a constant, nonvanishing ionic microfield, two maxima occur. The calculations have been performed for

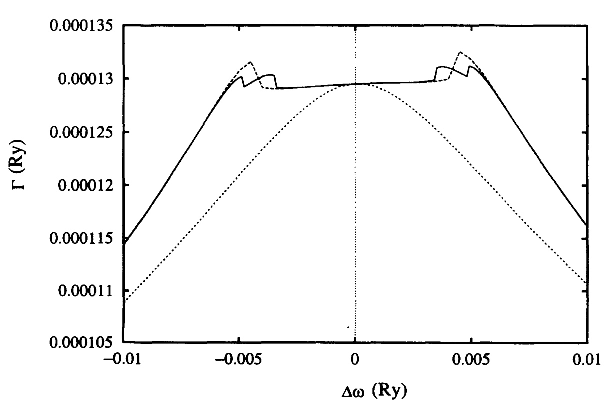

FIG. 1. Imaginary part of the width of the central L_α component including the following: — — —, dynamic screening (vanishing ionic microfield); ——, dynamic screening (averaged ionic microfield, $\beta=1$); and · · · ·, static Debye screening.

an electron density of 2.1×10^{18} cm^{-3} and $T=10^5$ K. It has been found, however, that the magnitude of the resonance maxima depends only weakly on density and temperature.

Considering the results, it can be concluded that the impact approximation is appropriate if $\Delta\omega<\omega_{\mathrm{pl}}$. If Eq. (6) is fulfilled, the width is determined by collective plasma oscillations causing a resonance peak and a succeeding steep decrease. For thermal plasmas, however, this does not cause any visible resonance structures on the line profile. The reason for this is the small magnitude of the resonances and the averaging procedure with the microfield distribution when calculating the line profile.

IV. NONTHERMAL EFFECTS ON THE LINE PROFILE

In Sec. III it has been shown that the collective dynamic screening of the electron-electron interaction leads to small bumps at frequencies given by Eq. (6). Unfortunately, no structure on the line profile is to be seen because it is smeared out by averaging over the ionic microfield.

In this section we investigate whether the resonances found in Sec. III will be increased in nonthermal plasmas. It is well known that a current in a plasma due to an external field leads to a relative drift between the electrons and ions. The cross section for collisions between the accelerated electrons and plasma particles decreases with higher electron energies. That is why hot electrons are more strongly accelerated by the external field. Further, it has been shown [12,13] that those electrons whose velocity is close to the phase velocity of the ion-wave oscillations can be strongly accelerated. However, most of the electrons have a smaller drift velocity than the phase velocity of the ion-wave fluctuations, at least for the experimental plasma parameters chosen in [1]. Therefore, besides the acceleration due to the external field, only some hot electrons may be accelerated further due to ion-wave oscillations. This effect should cause a velocity distribution function with a nonthermal high velocity tail.

For further calculations, such a velocity distribution will be modeled by a two-temperature electron gas [14] as in [10]. The velocity distribution function of the majority of the electrons with density n_1 is a Maxwellian one with temperature T_1. Only a small number of accelerated electrons are described by a Maxwellian distribution with

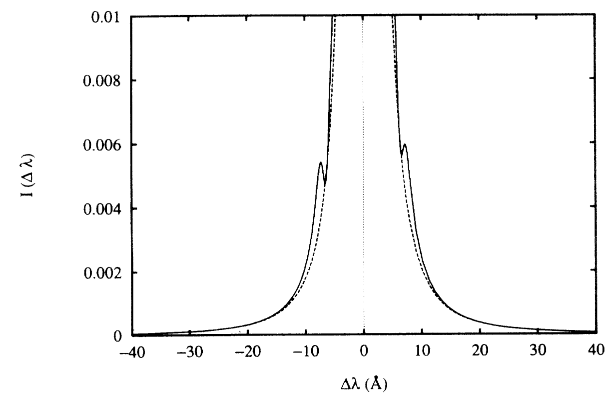

FIG. 2. Profile of the hydrogen L_α line: — — —, for thermal plasmas; ——, for weakly nonthermal plasmas.

temperature $T_2 \gg T_1$. Their density is much smaller than that of the thermal electrons ($n_2 \ll n_1$).

Using such a model for the velocity distribution function, the dielectric function $\varepsilon(\mathbf{q},\omega)$ is given by a superposition of the contributions resulting from both electronic subsystems. Introducing this dielectric function into Eq. (2) and calculating spectral line profiles according to [7], one may really find dips on the line profile.

In this paper, for example, the profile of the hydrogen Lyman-α line has been calculated for the plasma parameters $n_e = 2\times10^{18}$ cm^{-3} and $T = 40\,000$ K, which are similar to those chosen in the experiment of [1]. In Fig. 2 the hydrogen Lyman-α line is given. The profile has been calculated for $n_2/n_1 = 10^{-3}$ and $T_2/T_1 = 5000$. Dips are plainly visible near the electron plasma frequency. Figure 3 shows the structure of the dips for various densities of the hot electrons. It can be seen that more hot electrons produce a stronger structure on the line profile. However, the position of the dip remains at the electron plasma frequency. Further, it becomes obvious that the dip structure on the line profile looks very similar to that measured by Oks, Böddeker, and Kunze [1].

V. CONCLUSIONS

A many-particle approach has been applied to investigate the influence of resonance effects due to plasma oscillations on the line profile. It has been found that for slightly nonthermal plasmas, one may find dips on the Lyman-α line profile at the electron plasma frequency.

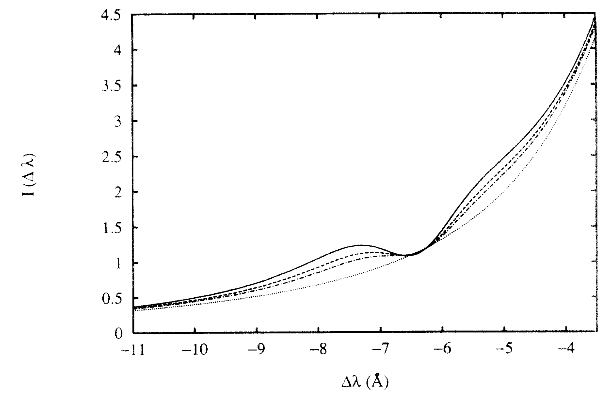

FIG. 3. Structure of the dips on the L_α profile for various densities of hot electrons. The parameters for the model of the velocity distribution function are $T_2/T_1 = 5000$. ——, $n_2/n_1 = 0.001$; — — —, $n_2/n_1 = 10^{-6}$; —·—·—·, $n_2/n_1 = 10^{-10}$; · · · ·, $n_2/n_1 = 0$.

The position as well as the shape of the calculated dips agree very well with experimental results [1].

Dips of higher orders, that is, at multiples of the electron plasma frequency, could not be found within the developed theory. In order to describe such higher-order dips also, the theory has to go beyond the applied linear response approximation. However, dips of higher than second orders should only be important for unstable plasmas. For such plasmas, of course, a consequent nonequilibrium theory has to be applied assuming that the radiating atoms interact only with the collective field of the turbulent plasma [8].

The theory presented is able to give the full line profile including dips due to the interaction of the radiator with electron plasma oscillations. Therefore, it is possible to estimate the magnitude of the resonance effect for various plasma conditions. Further, it should be possible to investigate whether there are dips on lines other than hydrogen L_α. Finally, as already discussed in [1], the measurement of the dips' position on the line profile could be an additional method for the measurement of high electron densities, at least for weak nonthermal plasmas.

ACKNOWLEDGMENT

This work was supported by the Sonderforschungsbereich 198.

[1] E. A. Oks, St. Böddeker, and H.-J. Kunze, Phys. Rev. A **44**, 8338 (1991).

[2] H.-J. Kusch, A. Döhrn, P. Nowack, and V. Helbig, in *Spectral Line Shapes,* edited by R. Stamm and B. Talin (Nova Science, Commack, NY, 1993), p. 149.

[3] A. Cohn, P. Bakshi, and G. Kalman, Phys. Rev. Lett. **29**, 324 (1972).

[4] H. W. Drawin, in *Spectral Line Shapes,* edited by B. Wende (De Gruyter, Berlin, 1981), p. 527.

[5] V. Gawrilenko and E. A. Oks, Fiz. Plazmy **13**, 39 (1987) [Sov. J. Plasma Phys. **13**, 1 (1987)].

[6] W. R. Rutgers and H. W. Kalfsbeek, Z. Naturforsch. Teil A **30**, 739 (1975).

[7] S. Günter, L. Hitzschke, and G. Röpke, Phys. Rev. A **44**, 6834 (1991).

[8] H. Capes and D. Voslamber, Phys. Rev. A **15**, 1751 (1977).

[9] St. Böddeker, S. Günter, A. Könies, L. Hitzschke, and H.-J. Kunze, Phys. Rev. E **47**, 2785 (1993).

[10] W. R. Chappell, J. Cooper, and E. W. Smith, J. Quant. Spectrosc. Radiat. Transfer **10**, 1195 (1970).

[11] J. Dawson and C. Oberman, Phys. Fluids **1**, 517 (1962).

[12] J. M. Dawson, Phys. Fluids **4**, 869 (1979).

[13] M. Nambu and P. K. Shukla, Phys. Rev. A **20**, 2498 (1979).

[14] D. A. Tidman and T. H. Dupree, Phys. Fluids **8**, 1860 (1965).