Parametric instabilities in quantum plasmas with electron exchange–correlation effects*

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Parametric instabilities induced by the nonlinear interaction between high frequency quantum Langmuir waves and low frequency quantum ion-acoustic waves in quantum plasmas with the electron exchange–correlation effects are presented. By using the quantum hydrodynamic equations with the electron exchange–correlation correction, we obtain an effective quantum Zaharov model, which is then used to derive the modified dispersion relations and the growth rates of the decay and four-wave instabilities. The influences of the electron exchange–correlation effects and the quantum effects on the existence of quantum Langmuir waves and the parametric instabilities are discussed in detail. It is shown that the electron exchange–correlation effects and quantum effects are strongly coupled. The quantum Langmuir wave can propagate in quantum plasmas only when the electron exchange–correlation effects and the quantum effects satisfy a certain condition. The electron exchange–correlation effects tend to enhance the parametric instabilities, while quantum effects suppress the instabilities.

Keywords: parametric instabilities, quantum Langmuir waves, electron exchange–correlation

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1. Introduction

In recent years, a great deal of attention has been focused on plasma instability.[1–5] A variety of instabilities exist in plasmas because due to their complexity, these include parametric instabilities, Jean's instabilities, two and three stream instabilities, and so on. In particular, the nonlinear coupling between Langmuir waves and ion-acoustic waves leads to many kinds of unstable phenomena, including the decay instability, the four-wave instability, the modulational instability, etc. Furthermore, the investigation of plasmas instabilities has been greatly advanced in quantum plasmas;[6–11] it is found that quantum effects have a significant influence on the instability.

In fact, parametric instabilities induced by the interplay between high frequency Langmuir waves and low frequency ion-acoustic waves are closely related to plasma interaction. It is well known that the interaction between electrons can be separated into a Hartree term due to the electrostatic potential of the total electron density and an electron exchange–correlation term. The exchange–correlation potential energy can, in general, be described as an unknown functional of the electron density,[12,13] and was first introduced by Kohn and Sham.[13] In ordinary circumstances, the electron exchange–correlation effects are often neglected because they are very weak. However, the role of the electron exchange–correlation effects become important when the electron density is high or the electron temperature is low,[14] such as in ultrasmall electronic devices, dense astrophysical plasmas, and laser plasmas. We expect that in these systems, both the quantum effects and the electron exchange–correlation effects would play important roles. The local density approximation (LDA) has been used very successfully to obtain the different forms of the electron exchange–correlation potential,[15,16] and given good results for conduction electrons in silicon inversion layers, GaAs/$G_{1-x}Al_xAs$ heterostructures and quantum wells.[17] Especially, the electron exchange–correlation effects in dense strongly coupled multicomponent plasmas,[18] typical Al–ion immersed plasma system,[19] and quantum plasmas with average atoms and superconfigurations[20] have also been discussed. It has been shown that the exchange–correlation potential has a significant impact in the plasma systems. Importantly, in a recent work,[21] a novel attractive force between ions in quantum plasmas with the electron exchange–correlation effects was reported. As discussed in this work, the new force is attributed to the consideration of the quantum statistical pressure, the quantum Bohm potential, as well as the electron exchange and electron correlations. However, the influence of the electron exchange–correlation effects on parameter instabilities in quantum plasmas is still not clear. Therefore, in this paper, based on the modified quantum hydrodynamic equations with the electron exchange–correlation potential for the two-species charged plasmas particles, we first get an effective quantum Zakharov model describing the coupling of high frequency quantum Langmuir waves and low

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frequency quantum ion-acoustic waves. Then, the modified dispersion relations and the growth rates of parametric instabilities with the electron exchange–correlation term are obtained. The influences of the electron exchange–correlation effects and the quantum effects on parametric instabilities are discussed in detail. It is interestingly found that the quantum effects and the electron exchange–correlation effects are strongly coupled and have a significant influence on parametric instabilities. The electron exchange–correlation effects tend to enhance the parametric instabilities, while the quantum effects suppress the instabilities.

2. Model and linear Langmuir waves

Let us consider the one-dimensional (1D) quantum hydrodynamical (QHD) equations with the electron exchange–correlation potential for the two-species quantum plasmas, composed of electrons and ions. The QHD equations consisting of the continuity and momentum balance equations are[7,14,22,23]

$$\frac{\partial n_e}{\partial t}+\frac{\partial}{\partial x}(n_e u_e)=0, \tag{1}$$

$$\frac{\partial n_i}{\partial t}+\frac{\partial}{\partial x}(n_i u_i)=0, \tag{2}$$

$$\begin{aligned}\frac{\partial u_e}{\partial t}+u_e\frac{\partial u_e}{\partial x}=&-\frac{e}{m_e}E-\frac{1}{m_e n_e}\frac{\partial P_e}{\partial x}\\&+\frac{\hbar^2}{2m_e^2}\frac{\partial}{\partial x}\left(\frac{\partial^2\sqrt{n_e}/\partial x^2}{\sqrt{n_e}}\right)\\&+\frac{1}{m_e}\frac{\partial V_{xc}}{\partial x},\end{aligned} \tag{3}$$

$$\frac{\partial u_i}{\partial t}+u_i\frac{\partial u_i}{\partial x}=\frac{e}{m_i}E. \tag{4}$$

Equations (1)–(4) are coupled by the Poisson equation

$$\frac{\partial E}{\partial x}=\frac{e}{\varepsilon_0}(n_i-n_e), \tag{5}$$

where subscripts e and i stand for electrons and ions, respectively. $m_{e,i}$, $n_{e,i}$, and $u_{e,i}$ represent the mass, density, and fluid velocity of electrons and ions, respectively. E is the electric field, ε_0 is the vacuum dielectric, $\hbar$ is the Planck constant divided by 2π. The pressure term P_e appearing in Eq. (3) must be related to the electron density n_e via an equation of state (EOS) in order to close our system of electron fluid, and depends on the thermodynamic properties of the system. In general, we assume ions to be pressureless and electrons to be isothermal, and with $P_e=k_B n_e T_e$. Here, k_B is the Boltzmann constant and T_e is the electron temperature. In addition, the third term on the right-hand side of Eq. (3) is the so-called Bohm potential, corresponding to the quantum correction of the density fluctuation, and contains all the quantum effects in the model.

In Eq. (3), V_{xc} is the exchange–correlation potential. In the adiabatic local-density approximation (ALDA), the exchange and correlation terms can be described as functionals of the time-dependent electron density n_e.[14] Hohenberg, Kohn and Sham[12,13] have shown that the density distribution of an interacting electron gas under an external field can be obtained by a one-body Schrödinger-type equation containing an exchange–correlation potential V_{xc} in addition to the usual Hartree potential and the external potential. The exchange–correlation potential V_{xc} is given by

$$V_{xc}=0.985\frac{e^2}{\varepsilon}\left[1+\frac{0.034}{a_B^* n^{1/3}}\ln(1+18.376a_B^* n^{1/3})\right],^{[24]}$$

where $a_B^*=\varepsilon\hbar^2/m_e e^2$, $\varepsilon=4\pi\varepsilon_0$ is the effective dielectric. Then we assume ions to be motionless and the homogeneous equilibria are $n_e=n_i=n_0$, $u_e=0$, and $E=0$. Linearizing Eqs. (1), (3), and (5) by splitting every relevant physical quantity into its equilibrium and perturbed components, $n_e=n_0+n_{e1}$, $u_e=u_{e1}$, and $E=E_1$. As a result, we obtain the following dispersion relation:

$$\omega^2=\omega_e^2+(v_e^2-v_c^2)k^2+\frac{\hbar^2}{4m_e^2}k^4, \tag{6}$$

where, ω is the wave frequency, k is the wave number, $\omega_e=(n_0e^2/m_e\varepsilon_0)^{1/2}$ is the electron plasma frequency, and $v_e=(\kappa_B T_e/m_e)^{1/2}$ is the electron thermal velocity. We define

$$v_c=\left[0.533\frac{n_0^{1/3}e^2}{m_e\varepsilon}(1-7.063\frac{n_0^{1/3}\hbar^2\varepsilon}{m_e e^2})\right]^{1/2}.$$

Equation (6) is the quantum version of the Langmuir dispersion relation with the electron exchange–correlation effects. Interestingly, one finds that the electron exchange–correlation effects modify the dispersion relation and the dynamics of Langmuir waves significantly. Especially, when $\hbar\to 0$ and $v_c\to v_e$, $\omega\to\omega_e$, and the Langmuir wave cannot propagate in quantum plasmas. Furthermore, for the general case, the critical condition for propagating Langmuir waves in quantum plasmas should be

$$v_e^2-v_c^2+\frac{\hbar^2}{4m_e^2}k^2>0.$$

That is,

$$A<1+H^2k^2, \tag{7}$$

where, the electron exchange–correlation term $A=v_c^2/v_e^2$, quantum term $H=\hbar\omega_i/\kappa_B T_e$, $\omega_i=(n_0e^2/m_i\varepsilon_0)^{1/2}$. That is, the quantum Langmuir wave can propagate in a quantum plasma only when the electron exchange–correlation effects and the quantum effects satisfy relation (7). However, under this condition, we cannot clearly see the influence of the electron exchange–correlation effects on the parametric instabilities, because ω is real. Therefore, we will use the quantum hydrodynamic equations to get the available model in the following section.

3. Quantum Zakharov model

In this section, we employ the two-time scale theory[5,7] to study the nonlinear interaction between the high frequency quantum Langumuir waves and the low frequency quantum ion-acoustic waves. All quantities are separated into high frequency (subscript h) and low frequency (subscript l) components, $n_{\rm e}(x,t) = n_0 + n_{\rm l}(x,t) + n_{\rm h}(x,t)$, $n_{\rm i}(x,t) = n_0 + n_{\rm l}(x,t)$, $u_{\rm e}(x,t) = u_{\rm l}(x,t) + u_{\rm h}(x,t)$, $u_{\rm i}(x,t) = u_{\rm l}(x,t)$, $E(x,t) = E_{\rm l}(x,t) + E_{\rm h}(x,t)$. The high frequency parts are neglected for ions, because the mass of ions is much larger than electrons. We also assume that departures from the quasineutral regime ($n_{\rm i} \approx n_{\rm e}$, $u_{\rm i} \approx u_{\rm e}$) are provided only by the high frequency components of the electrons motion. We write the fast time scale electric field in the form $E_{\rm h}(x,t) = \widetilde{E}(x,t)(\mathrm{e}^{-\mathrm{i}\omega_{\rm e}t} + \mathrm{e}^{\mathrm{i}\omega_{\rm e}t})/2$, here, $\widetilde{E}(x,t)$ is the slowly varying envelope of the high frequency electric field. Then combining the high frequency parts of Eqs. (1)–(5) and ignoring the term $\partial_t^2\widetilde{E}$ due to $\partial_t^2\widetilde{E} \ll \omega_{\rm e}\partial_t\widetilde{E}$, we obtain the following equation which describes the evolution of the slowly varying amplitude $\widetilde{E}$

$$\mathrm{i}\frac{\partial\widetilde{E}}{\partial t} + \frac{1}{2}\frac{v_{\rm e}^2 - v_{\rm c}^2}{\omega_{\rm e}}\frac{\partial^2\widetilde{E}}{\partial x^2} - \frac{\hbar^2}{8m_{\rm e}^2\omega_{\rm e}}\frac{\partial^4\widetilde{E}}{\partial x^4} = \frac{\omega_{\rm e}}{2}\frac{n_{\rm l}}{n_0}\widetilde{E}. \tag{8}$$

In order to get a set of equations describing low frequency components of the quantum hydrodynamical equations, we take a time-averaging method[5] to the high frequency quantities, and obtain

$$\frac{\partial n_{\rm l}}{\partial t} + n_0\frac{\partial u_{\rm l}}{\partial x} = 0, \tag{9}$$

$$\frac{\partial u_{\rm l}}{\partial t} + \left[\frac{\kappa_{\rm B}T_{\rm e}}{n_0 m_{\rm e}} - 0.533\frac{n_0^{-2/3}e^2}{m_{\rm e}\varepsilon}\left(1 - 7.063\frac{n_0^{1/3}\hbar^2\varepsilon}{m_{\rm e}e^2}\right)\right]\frac{\partial n_{\rm l}}{\partial x} + \frac{e}{m_{\rm e}}E_{\rm l} - \frac{\hbar^2}{4m_{\rm e}^2 n_0}\frac{\partial^3 n_{\rm l}}{\partial x^3} + \frac{e^2}{4m_{\rm e}^2\omega_{\rm e}^2}\frac{\partial|\widetilde{E}|^2}{\partial x} = 0, \tag{10}$$

$$\frac{\partial u_{\rm l}}{\partial t} - \frac{e}{m_{\rm i}}E_{\rm l} = 0. \tag{11}$$

In Eq. (10), all convective terms were neglected under the assumption that Langmuir waves are weak turbulence. Taking $m_{\rm e} \ll m_{\rm i}$, one gets

$$\frac{\partial^2 n_{\rm l}}{\partial t^2} - (c_{\rm s}^2 - c_{\rm c}^2)\frac{\partial^2 n_{\rm l}}{\partial x^2} + \frac{\hbar^2}{4m_{\rm i}m_{\rm e}}\frac{\partial^4 n_{\rm l}}{\partial x^4} = \frac{\varepsilon_0}{4m_{\rm i}}\frac{\partial^2|\widetilde{E}|^2}{\partial x^2}, \tag{12}$$

where $c_{\rm s} = (\kappa_{\rm B}T_{\rm e}/m_{\rm i})^{1/2}$ is the ion-acoustic velocity, and we define

$$c_{\rm c} = \left[0.533\frac{n_0^{1/3}e^2}{m_{\rm i}\varepsilon}\left(1 - 7.063\frac{n_0^{1/3}\hbar^2\varepsilon}{m_{\rm i}e^2}\right)\right]^{1/2}.$$

Equations (8) and (12) are the quantum Zakharov equations with the electron exchange–correlation effects. Normalizing Eqs. (8) and (12) with $\bar{x} = 2\sqrt{m_{\rm e}/m_{\rm i}}x/\lambda_{\rm e}$, $\bar{t} = 2(m_{\rm e}/m_{\rm i})\omega_{\rm e}t$, $\bar{n} = m_{\rm i}n_{\rm l}/(4m_{\rm e}n_0)$, and $\bar{E} = \sqrt{\varepsilon_0 m_{\rm i}/(16m_{\rm e}n_0\kappa_{\rm B}T_{\rm e})}\widetilde{E}$, here, $\lambda_{\rm e} = v_{\rm e}/\omega_{\rm e}$ is electron Debye length. In order to simplify, we drop bars and subscripts in the notation, and write Eqs. (8) and (12) as the following forms

$$\mathrm{i}\frac{\partial E}{\partial t} + (1-A)\frac{\partial^2 E}{\partial x^2} - H^2\frac{\partial^4 E}{\partial x^4} = nE, \tag{13}$$

$$\frac{\partial^2 n}{\partial t^2} - (1-A)\frac{\partial^2 n}{\partial x^2} + H^2\frac{\partial^4 n}{\partial x^4} = \frac{\partial^2|E|^2}{\partial x^2}. \tag{14}$$

When $A = 0$, equations (13) and (14) reduce to the ordinary quantum Zakharov equations.[7,25] It can be seen that the electron exchange–correlation parameter A depends on the electrons temperature $T_{\rm e}$ and the equilibrium particle number density n_0. For dense or low temperature plasmas, the value of A should larger. In general, for electrons density $n_0 \sim 10^{22}$ m^{-3}, the electrons temperature $T_{\rm e} \sim 10^2$ K, we estimate the electron exchange–correlation parameter $A \sim 10^{-1}$, quantum parameter $H \sim 10^{-2}$, respectively. For a lower mass of the electrons, H would increase greatly and $H \sim 10^{-1}$.[7] For sufficiently larger electrons density, $A \to 1$ and even $A > 1$, the dynamics and stabilities of Langmuir waves and ion-acoustic waves coupled by Eqs. (13) and (14) would be modified significantly. That is, the electron exchange–correlation effects would be important, this will be confirmed by studying the parametric instabilities given in the following section.

4. Decay instability

Now we consider decay instability. To acquire the growth rate of the decay instability we compose a primary Langmuir wave and its longitudinal perturbation, $E = E_0\mathrm{e}^{\mathrm{i}(k_0x - \omega_0t)} + E_1\mathrm{e}^{\mathrm{i}(k_1x - \omega_1t)}$, and an ion-acoustic wave $n = n_1(t)\cos(Kx - \Omega t)$. And according to Eqs. (13) and (14), we can obtain the dispersion relation of the quantum Langmuir wave and the quantum ion-acoustic wave, respectively.

$$\omega_0 = (1-A)k_0^2 + H^2k_0^4, \tag{15}$$

$$\omega_1 = (1-A)k_1^2 + H^2k_1^4, \tag{16}$$

$$\Omega^2 = (1-A)K^2 + H^2K^4. \tag{17}$$

Then we can use parameter resonant conditions $k_0 = k_1 + K$, $\omega_0 = \omega_1 + \Omega$, which meet momentum and energy conservation respectively. Furthermore, linearizing Eqs. (13) and (14), we have

$$\mathrm{i}\dot{E}_1 e_1 = \frac{E_0 n_1}{2}(e_+ + e_-)e_0, \tag{18}$$

$$\left(\frac{\ddot{n}_1}{2} - \mathrm{i}\Omega\dot{n}_1 + K^2E_0E_1^*\right)e_+ + \left(\frac{\ddot{n}_1}{2} + i\Omega\dot{n}_1 + K^2E_0^*E_1\right)e_- = 0. \tag{19}$$

For the sake of simplicity, we use the notation $e_{0,1} = \exp[\mathrm{i}(k_{0,1}x - \omega_{0,1}t)]$, $e_\pm = \exp[\pm\mathrm{i}(Kx - \Omega t)]$. Taking the resonance part of Eqs. (18) and (19), and $\dot{E}_1 = \mathrm{i}\omega E_1$, one obtains

the dispersion relation

$$\omega^3 + 2\Omega\omega^2 + K^2|E_0|^2 = 0. \tag{20}$$

In Eq. (20), ω^3 can be neglected because of $\Omega \gg |\omega|$, letting $\omega = \mathrm{i}\gamma$, and using Eq. (17) we get the growth rate

$$\gamma = \frac{\sqrt{K}|E_0|}{\sqrt{2}(1 - A + H^2K^2)^{1/4}}. \tag{21}$$

According to Eq. (21), when $K \to \infty$ or $A \to 1$, $\gamma = \gamma_{\max} = |E_0|/\sqrt{2H}$. That is, when $A < 1$ the maximum growth rate $\gamma_{\max}$ is not affected by the electron exchange–correlation effects, but by the quantum effects. However, when $A \to 1$, the growth rate is independent of wave number. As discussed in Section 2, the existence of the propagating Langmuir waves in quantum plasmas needs $A < 1 + H^2K^2$. These can be clearly seen in Fig. 1. Figure 1 shows the growth rate of the decay instability for different A, H, and K. It is clear that, the electron exchange–correlation effects A enhance the instability growth rate, while the quantum effects suppress the growth rate. When $K \to \infty$ or $A \to 1$, $\gamma \to \gamma_{\max}$. For sufficiently strong quantum effects, the influence of the electron exchange–correlation effects is weakened. For fixed H, the electron exchange–correlation effects play an important role for relatively long wave-length perturbation (i.e., with small K). On the other hand, the electron exchange–correlation effects and the quantum effects strongly couple and have a significant influence on the decay instability.

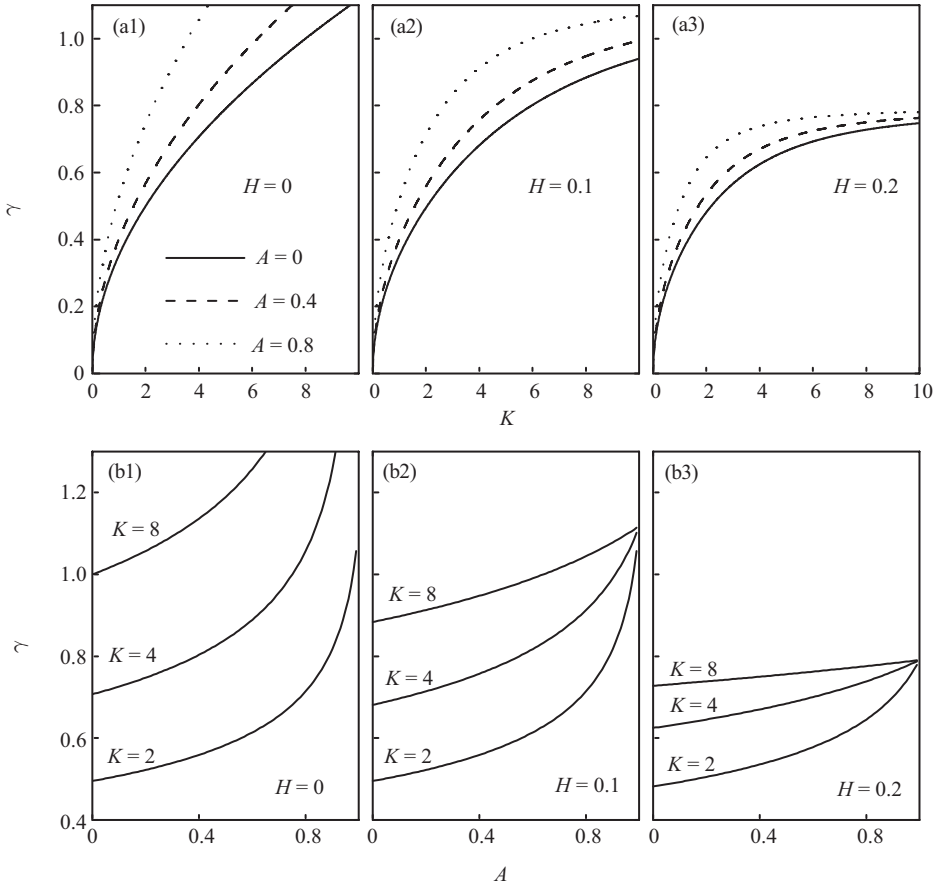


Fig. 1. (al)–(a3): the growth rate of the decay instability against K for different A and H, (b1)–(b3): the growth rate of the decay instability against A for different K and H. $E_0 = 0.5$.

5. Four-wave instability

Let us consider the four-wave instability. The Langmuir waves are governed by an equilibrium Langmuir wave and two perturbations which are the longitudinal and transverse field,[5,7] taking $E(x,t) = E_0\exp(-\mathrm{i}\omega_0 t + \mathrm{i}k_0 x) + E_+\exp[-\mathrm{i}(\omega_0+\omega)t + \mathrm{i}(k_0+k)x] + E_-\exp[-\mathrm{i}(\omega_0-\omega^*)t + \mathrm{i}(k_0-k)x]$, and an ion-acoustic wave $n(x,t) = \tilde{n}\exp(-\mathrm{i}\omega t + \mathrm{i}kx) +$ c.c., where c.c. refers to complex conjugate. Then, from Eqs. (13) and (14) and

$$\omega_0 = (1-A)k_0^2 + H^2k_0^4$$

we obtain the following dispersion relation

$$D_s D_1 D_2 = k^2 E_0^2 (D_1 + D_2), \tag{22}$$

where

$$D_s = \omega^2 - (1-A)k^2 - H^2k^4,$$

$$D_1 = \omega - (1-A)(k^2+2k_0k) - H^2(k^4+4k_0k^3+6k_0^2k^2+4k_0^3k),$$
$$D_2 = -\omega - (1-A)(k^2-2k_0k) - H^2(k^4-4k_0k^3+6k_0^2k^2-4k_0^3k).$$

The dispersion relation (22) is a fourth-order polynomial about ω. In general, it is difficult to get its solution, we can only analyze it numerically. In order to reveal the role of the electron exchange–correlation effects in the four-wave interaction process, we first discuss the simplest case of $k_0 = 0$. With $\omega = \mathrm{i}\gamma$, the dispersion relation becomes

$$[\gamma^2+(1-A)k^2+H^2k^4][\gamma^2+((1-A)k^2+H^2k^4)^2] = 2k^2E_0^2[(1-A)k^2+H^2k^4]. \quad (23)$$

Solving γ^2 from Eq. (23), we get the growth rate

$$\gamma^2 = -\frac{1}{2}k^2(1-A+H^2k^2)[1+(1-A+H^2k^2)k^2] + \frac{1}{2}k^2(1-A+H^2k^2)\left\{[1-(1-A+H^2k^2)k^2]^2 + \frac{8E_0^2}{1-A+H^2k^2}\right\}^{1/2}. \quad (24)$$

From Eq. (24), we should note that

$$A > 1 - \frac{\sqrt{2}E_0 - H^2k^2}{k}. \quad (25)$$

When equations (7) and (25) are satisfied, the square of the growth rate $\gamma^2 > 0$, the system is unstable because ω is imaginary. On the other hand, the electron exchange–correlation effects strongly modify the instability of the system. Figure 2 shows γ^2 against k^2, the influences of A and H on the square of the growth rate γ^2 are displayed. We can find that the instability region ($\gamma^2 > 0$) expends with increasing A, but contracts with increasing H. It is important to note that the electron exchange–correlation effects change the maximum of γ^2. The influence of the electron exchange–correlation effects on four-wave instability is still significant for large H (this differs from the result of the decay instability). That is, the quantum effects tend to suppress the maximum γ^2 and the instability region, while the electron exchange–correlation effects enhance the maximum of γ^2 and the instability region. For the general four-wave interaction process with $k_0 \neq 0$, the influences of A, k_0, E_0, and H are displayed in Figs. 3 and 4. The influence of A and H on the instability is similar to the case of $k_0 = 0$: the instability region expands with increasing A and k_0, but contracts with increasing H. However, for sufficiently strong quantum effects, the influence of the electron exchange–correlation effects on instability is weakened. That is, the effects of quantum and electron exchange–correlation effects are coupled.

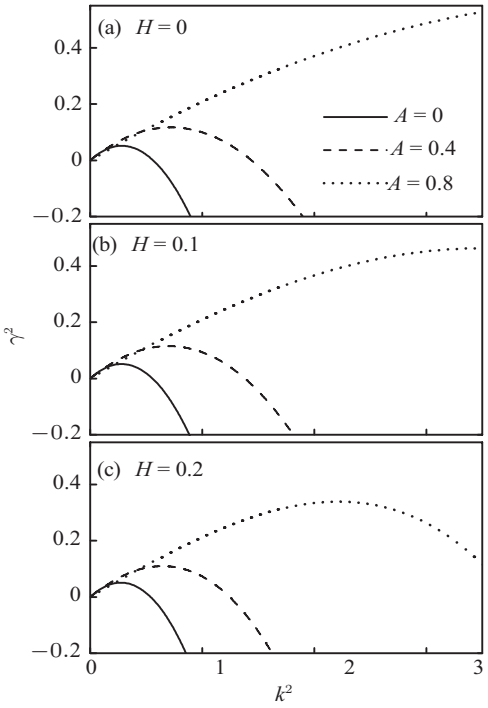


Fig. 2. γ^2 as a function of k^2 in the dispersion relation with the exchange–correlation effects for the four-wave instability. $E_0 = 0.5$.

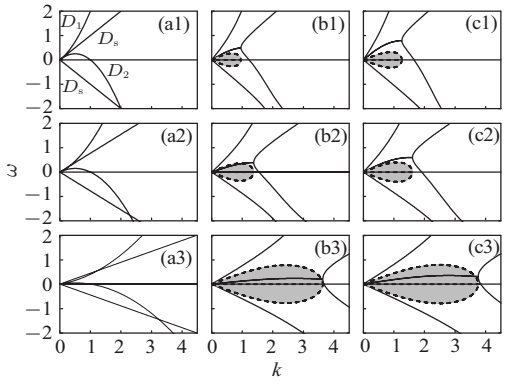


Fig. 3. The frequency ω (solid lines represent real parts, dashed lines represent imaginary parts) against k for different A, k_0, and E_0. The shadow region refers to the unstable region. From the top row to the bottom row, $A = 0.0$, $A = 0.4$, and $A = 0.8$. The first column (uncoupled cases), $E_0 = 0.0$, the second and third columns (coupled cases), $E_0 = 0.5$. The first and second columns for $k_0 = 0.5$, the third column for $k_0 = 0.75$. D_s, D_1, and D_2 indicate the branches of Eq. (21), respectively. $H = 0.0$.

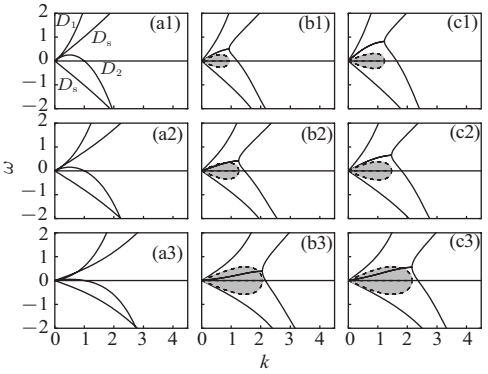


Fig. 4. Functions and parameters are the same as those in Fig. 3, but with $H = 0.2$.

6. Conclusions

In this paper, we have investigated the parametric instabilities induced by the interplay between high frequency quantum Langmuir waves and low frequency quantum ion-acoustic waves in quantum plasmas with the electron exchange–correlation effects. The modified quantum Zakharov model with the electron exchange–correlation correction is obtained by using one-dimensional quantum hydrodynamic equations and the two-time scale theory. We obtained the modified dispersion relations and the growth rates of the decay and four-wave instabilities. We have found that the electron exchange−correlation effects and quantum effects play vital role when the electron density is high or the electron temperature is low. The electron exchange–correlation effects and the quantum effects are coupled strongly. The existence of quantum Langmuir waves and the parametric instabilities closely depend on the electron exchange–correlation effects and the quantum effects. The electron exchange–correlation effects tend to enhance the parametric instabilities, while the quantum effects suppress the instabilities. We expect that our work can be achieved in the future experiment.

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