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Dressed ion acoustic solitary waves in quantum plasmas with two polarity ions and relativistic electron beams

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A B S T R A C T

A theory for dressed quantum ion acoustic waves (QIAWs), which includes higher-order corrections when QIAWs are investigated by the reductive perturbation method, is presented for unmagnetized plasmas containing positive and negative ions and weakly relativistic electron beams. The properties of the QIAWs are investigated using a quantum hydrodynamic model, from which a Korteweg–de Vries equation is derived using the reductive perturbation method. An equation including higher-order dispersion and nonlinearity corrections is also derived, and the physical parameter space is discussed for the importance of these corrections.

1. Introduction

Quantum effects in plasmas have important applications to the next-generation intense laser–solid density plasma interaction [1], quantum X-ray free electron lasers [2,3], semiconductors and micromechanical devices, and compact astrophysical object [4] such as white dwarf stars and neutron stars [5]. Due to the Pauli exclusion principle for fermions, quantum effects become important when the de Broglie wavelength of the electrons is comparable to the inter-electron distance. Due to the electrons degeneracy at equilibrium, they will obey the Fermi–Dirac distribution instead of the Boltzmann distribution.

Similar to classical plasmas, where fluid equations for electrostatic waves can be derived via moments of the Vlasov–Poisson system, quantum hydrodynamic (QHD) equations including the Bohm potential due to the quantum tunneling effect can be obtained via moments of the Wigner–Poisson system [6]. Linear and nonlinear collective excitations in quantum plasmas have been investigated including the effects of quantum tunneling, quantum statistic, as well as electron spin on the electrostatic acoustic and electromagnetic waves [7,8]. Among them, one of the most important nonlinear waves is the quantum ion acoustic wave (QIAW) which has applications to carbon nanotubes [9,10] and other laboratory and astrophysical settings, and which can be investigated using a QHD model for the inertial ions and inertialess electrons [11]. For QIAWs with small but finite amplitudes, a Korteweg–de Vries (KdV) equation can be derived and used to investigate quantum effects on ion-acoustic solitary waves [11,12]. The nonlinear wave modes are characterized by a quantum parameter H, which is proportional to the ratio between the plasmon energy $\hbar\omega_{pe}$ and the Fermi energy $k_B T_{Fe}$ with $\hbar$ being the Plank constant divided by 2π, k_B Boltzmann's constant, T_{Fe} the electron Fermi temperature, and ω_{pe} the electron plasmas frequency. For cylindrical and spherical geometry, the QIAW can be described by a modified KdV [13] or modified nonlinear Schrödinger [14] equation, while for QIAWs with arbitrary large amplitudes, pseudopotential techniques can instead be used [15]. The modulational instability of two-dimensional QIAW packets is strongly influenced by the quantum parameter at small scales [16]. For double layer structures of QIAWs, the quantum diffraction parameter reduces the steepness [17]. Quantum ion-acoustic shock waves can be formed in the presence of ion kinematic viscosity, but the shock can break up into solitary waves when the effects of viscosity are small [18]. Shock waves in cylindrical or spherical geometries have also been investigated [19]. Monopolar, dipolar, and vortex street-type QIAWs can form in magnetized quantum plasmas, where the quantum diffraction effects modifies the length scales of the vortices [20].

Quantum plasmas with positive and negative ions have also attracted much attention due to great potential applications of negative ions in microelectronic or photoelectronic industries [21]. Negative ions can also be produced by electron attachment to

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neutral particles or may be injected from external sources. The linear and nonlinear propagation of QIAWs have been investigated in the quantum pair-ion plasmas by considering the inertial ions and inertialess electrons [22]. Recently, the effects of negative ions on shock structures were also considered in a degenerate dissipative plasma, where the strength of the shock wave increases with the decrease of the negative ion density [23]. The phase shifts in the head-on collision of quantum dust ion acoustic solitons are also affected by the effects of quantum parameter H and the ratio of charge density of positive ions to that of negative ions in quantum pair-ion plasmas [24].

On the other hand, the physics of beam plasmas system have received a great deal of interest in understanding the basic properties of magnetospheric and solar physics. Nonlinear ion acoustic waves (IAWs) can be excited when an electron beam is injected into a plasma. In a classical plasmas with hot isothermal beam and electrons and warm ions, there are four ion acoustic waves modes and the corresponding rarefactive solitons with small amplitude waves [25]. While for IAWs with arbitrary amplitude, a pseudopotential method can be used to investigate the effect of electron beams on the IAWs, which shows that the existence of IAWs sensitively depend on density of electron beams that can reduce the propagation speed of the IAWs [26]. The modulational instability of the four distinct IAW modes has different behavior from each other, where the stability criteria depend on the velocity and density of the beam [27]. More recently, IAWs in an electron beam superthermal plasmas were investigated in the fully nonlinear regime, which showed that solitary waves with both negative and positive polarities can coexist, and that the speeds of the solitary waves depended on the temperature of the ions and superthermal electrons [28]. Recently linear instability for two stream quantum plasma was studied by multistream model derived from Klein–Gordon–Maxwell system [29]. The relativistic steam instability are important for the electron heating in intense laser plasma system [30], in rotating thermal viscous objects [31], and in astrophysical relativistic shocks [32].

However, very little work has been done on the effect of an electron beam on nonlinear QIAWs in a quantum plasma. We here investigate the QIAWs in quantum plasmas with two polarity ions, and relativistic electron beams. Higher-order nonlinearities modifies the solitary wave amplitude and can change its shape [33]. Ion acoustic solitons with higher-order corrections, called dressed solitons, was considered by including higher-order terms in the reductive perturbation method, and by using multiple space–time variables to derive the higher-order terms [34]. Dressed solitons obtained numerically contained high-frequency Langmuir field envelopes together with potential depressions that became oscillatory away from the interaction region [35]. Recently dressed soliton in quantum dusty pair-ion plasmas [36] and electron–positron–ion plasmas [37] have also been studied using a higher-order inhomogeneous differential equation, but without considering the effects of electron beams. Higher-order corrections to nonlinear waves were investigated by considering the effects of electron beams on the properties of compressive or rarefactive solitons [38] in classic plasmas. For quantum ion acoustic solitary waves with very small amplitude, the KdV equation with lowest-order nonlinearity and dispersion is good enough to describe the solitary waves. As the amplitude increases, the amplitude and width of solitons will deviate strongly from the prediction of the KdV equation [39]. Accordingly the higher-order nonlinear and dispersion effects must also be considered. In this Letter, we will investigate the properties of dressed QIAWs in the quantum plasma and to consider the combined effects of quantum diffraction, relativistic electron beams, and negative ions on the propagation of nonlinear QIAWs. By using numerical analysis we will discuss the physical condition to include the high-order corrections.

2. Basic equations

Let us consider a quantum plasma consisting of two polarity ions, and electron beams. The charge neutrality at equilibrium reads $n_{+0} = n_{e0} + n_{-0}$, where n_{+0}, n_{-0}, and n_{e0}, are the equilibrium number densities of the positive and negative ions, and electron beam, respectively. Collisions have been neglected between electrons and the two types of ions. We will assume that the particles obeys the one-dimensional zero temperature Fermi gas, and obey the pressure law $p_j = (m_j v_{Fj}^2/3n_{j0}^2)n_j^3$ [6], with $j = e, +, -$ standing for electrons, positive ions, and negative ions, respectively, and where m_j is the mass and $v_{Fj} = \sqrt{2k_B T_{Fj}/m_j}$ is the Fermi speed. The set of equations describing the dynamics of positive ions and negative ions are given as

$$\frac{\partial n_+}{\partial t} + \frac{\partial n_+ v_+}{\partial x} = 0, \tag{1}$$

$$\frac{\partial v_+}{\partial t} + v_+\frac{\partial v_+}{\partial x} = -\frac{\partial \phi}{\partial x} - \sigma_+ n_+ \frac{\partial n_+}{\partial x}, \tag{2}$$

$$\frac{\partial n_-}{\partial t} + \frac{\partial n_- v_-}{\partial x} = 0, \tag{3}$$

$$\frac{\partial v_-}{\partial t} + v_-\frac{\partial v_-}{\partial x} = \mu_-\frac{\partial \phi}{\partial x} - \sigma_- n_- \frac{\partial n_-}{\partial x}, \tag{4}$$

where n_+ and n_- are the number densities of the positive and negative ions, normalized by their equilibrium number densities n_{+0} and n_{-0}, respectively. Also, v_+ and v_- are the fluid velocities of the positive and negative ions, normalized by the quantum ion acoustic speed $c_{s+} = \sqrt{2k_B T_{Fe}/m_+}$, where k_B is Boltzmann's constant, T_{Fe} is the electron Fermi temperature, $\sigma_+ = T_{F+}/T_{Fe}$ is the ratio of the Fermi temperatures of the positive ions and electrons, $\sigma_- = \mu_- T_{F-}/T_{Fe}$ is the combined effects of the ratio of positive ion mass to the negative ion mass $\mu_- = m_+/m_-$ and the ratio of Fermi temperature of negative ions to that of electrons. On the ion time scale, the electron beams with a streaming velocity much larger than electron Fermi speed can be described by the fluid equations. We also have the following two equations for the beam electrons as

$$\frac{\partial n_e}{\partial t} + \frac{\partial n_e v_e}{\partial x} = 0, \tag{5}$$

$$\left(\frac{\partial}{\partial t} + v_e\frac{\partial}{\partial x}\right)(v_e\gamma_e) = \sigma_e\frac{\partial \phi}{\partial x} - \sigma_e n_e\frac{\partial n_e}{\partial x} + \frac{H_e^2 c_n^4}{2\gamma_e}\frac{\partial}{\partial x}\left(\frac{1}{\sqrt{n_e}}\frac{\partial^2\sqrt{n_e}}{\partial x^2}\right), \tag{6}$$

where $\gamma_e = (1 - v_e^2/c_n^2)^{-1/2}$ is the relativistic gamma factor for the electron beams. Here we have for convenience normalized the electron beam velocity v_e and speed of light in vacuum c_n by the quantum ion acoustic speed c_{s+}. In the weakly relativistic limit, the gamma factor can be written $\gamma = 1 - v_e^2/2c_n^2$. Here $\sigma_e = m_+/m_e$ is the mass-ratio between positive ions and electrons. The quantum parameter is $H_e = \hbar\omega_{p+}/m_e c^2$ for electrons. The electrostatic potential ϕ can be determined by Poisson's equation

$$\frac{\partial^2 \phi}{\partial x^2} = \mu n_- + (1-\mu)n_e - n_+, \tag{7}$$

where $\mu = n_{-0}/n_{+0}$ is the ratio between the equilibrium number densities of negative and positive ions. Here, ϕ is normalized by $2k_B T_{Fe}/e$, space is normalized by c_{s+}/ω_{p+} and time by the inverse positive ion plasma frequency $\omega_{p+}^{-1} = \sqrt{m_+/4\pi n_{+0}e^2}$.

We next use the reductive perturbation method to derive a KdV equation with higher-order corrections from Eqs. (1)–(7). We concentrate on the one-dimensional case. The stretched coordinates