Available online at www.sciencedirect.com
ScienceDirect
PHYSICS LETTERS A
Physics Letters A 364 (2007) 304–312
www.elsevier.com/locate/pla

Coupling between nonlinear Langmuir waves and electron holes in quantum plasmas

Dusan Jovanović [a,*], Renato Fedele [b]

[a] *Institute of Physics, P.O. Box 57, 11001 Belgrade, Serbia*
[b] *Dipartimento di Scienze Fisiche, Universitá Federico II di Napoli and INFN Sezione di Napoli, Complesso Universitario Monte S. Angelo, via Cintia, I-80126 Napoli, Italy*

Received 19 August 2006; received in revised form 1 November 2006; accepted 5 December 2006

Available online 14 December 2006

Communicated by F. Porcelli

Abstract

The nonlinear effects on a slow timescale, compared with the electron plasma frequency, are studied using the Wigner–Poisson system, in the plasma regimes characterized by the overlapping of the wavefunctions of individual electrons, by the presence of a large amplitude Langmuir pump wave, and whose temperature is higher than the Fermi temperature. It is shown that the electron trapping on closed orbits in phase space is strongly affected both by the classical nonlinear ponderomotive effects and by the quantum super-diffusion. A solution in the form of a quantum corrected electron hole is found in terms of a generalized energy in the Wigner equation that contains higher derivatives in velocity space. In the classical limit, the high-frequency pump hampers the electron trapping due to the unfavorable sign of the ponderomotive potential and due to deformation of their distribution function by the diffusion. Conversely, in the modulational regime the leading quantum effect is shown to be related with the effective super-diffusion in the velocity space associated with the quantum effects on the high-frequency pump, which facilitates the electron trapping and allows the creation of holes with smaller amplitudes.
© 2006 Elsevier B.V. All rights reserved.

PACS: 52.25.Dg; 52.35.Mw; 05.60.Gg

1. Introduction

In recent years, quantum effects in plasmas and in electronic devices have attracted a lot of interest, due to their engineering relevance for the interaction of ultrastrong laser pulses with dense plasmas, see [1] and references therein, in microelectronics and nanotechnologies, e.g. for the resonant tunneling diode [2], nanoelectron tubes (nanotriode) [3], and ultra-integrated devices, and also due to their theoretical relevance in astrophysics [4] (e.g. for electron–positron plasmas in pulsars etc.), as well as in the experiments with particles and anti-particles in combined traps used to form anti-hydrogen, which can be modeled by a plasma possessing quantum features [5]. The common characteristic of such systems is that the typical distance between particles is of the order of their de Broglie wavelength, when the overlapping of their individual wavefunctions takes place. The classical transport models are not sufficient to describe the plasma behavior in such devices adequately. The appropriate phase space description is provided by the Wigner–Moyal quasidistribution [6,7] whose evolution equation, the Wigner equation, plays the role of a kinetic-like equation associated with the system. In a plasma context, the hydrodynamic models derived as the moments of the Wigner equation, have been used successfully to describe the quantum ion acoustic waves [8], as well as the quantum Zakharov system [9], i.e. the nonlinear coupling between the quantum ion-acoustic waves and the quantum Langmuir waves.

* Corresponding author.
E-mail addresses: djovanov@phy.bg.ac.yu (D. Jovanović), renato.fedele@na.infn.it (R. Fedele).

0375-9601/$ – see front matter © 2006 Elsevier B.V. All rights reserved.
doi:10.1016/j.physleta.2006.12.015

In a recent paper [10], a kinetic theory of particles in quantum plasmas moving in their own, self-consistent potential was presented based on the Wigner–Poisson system of equations, and the nonlinear self-consistent solution of the Wigner–Poisson system was found assuming weak nonlinearity and proximity to the classical Vlasov–Poisson system. Such solution represents a quantum correction to the classical electron hole. The first theoretical description of classical electron holes, based on Maxwellian distributions, was published in [11], see also Refs. [12,13] and the review Ref. [14], while the trapping of high-frequency Langmuir wave field in a classical electron hole was presented in Ref. [15]. The electron holes have been shown to be remarkably stable coherent structures that can increase the plasma transport [16]. In particle accelerators, their existence has also been predicted [17, 18] and experimentally observed [19].

In this Letter we present a self-consistent description of the nonlinear structures arising due to the electron trapping on closed orbits in phase space, in plasma regimes that are characterized by a very small inter-electron distance, when the quantum uncertainty of the electron velocity and position cannot be ignored. In laboratory experiments, the quantum plasmas are often subjected to a laser field, such as the dense plasmas generated in the ultraintense laser–solid interaction [1]. Another example is the irradiation, with intense ultrashort laser beams, of the plasma in metallic nanostructures (metal clusters, nanoparticles, thin metal films) [20], in order to probe the electron dynamics which occurs on the femtosecond scale. Thus, in the study of the nonlinear phenomena in typical quantum plasmas, one needs to account also for the effects of high-frequency radiation such as the radiation pressure, ponderomotive force and the quasilinear diffusion.

In contrast to the earlier study [10], in which the quantum effects (in the absence of a Langmuir pump) were treated as a small perturbation, we find a full solution in terms of a generalized integral of motion (generalized energy) of the Wigner equation that contains higher derivatives in velocity space. Such solution is correct up to the second order in the ratio of the electron potential and thermal energies, $e\phi/T$. It is demonstrated that in the classical limit, the high-frequency pump wave is trapped in the density depletion associated with the electron hole. However, the presence of the pump reduces the electron trapping due to the unfavorable sign of the ponderomotive potential and due to deformation of the electron distribution function by the quasilinear diffusion in velocity space. Conversely, for a short wavelength pump, the leading quantum effect is shown to come from the electron hyper-diffusion in velocity space associated with the quantum effects on the high-frequency Langmuir pump. In contrast to the electron tunneling on the slow scale studied in Ref. [10], the quantum quasilinear hyper-diffusion facilitates the electron trapping and allows the creation of holes with smaller amplitudes.

2. Basic equations

We study nonlinear phenomena in a one-dimensional quantum plasma, whose electron temperature is much higher than the corresponding Fermi energy. In other words, we assume that the electrons are essentially free particles, but their average distance is so small that an overlapping between their individual wave functions takes place. The electron gas is electrostatically neutralized by the ion background. We consider the characteristic temporal scale on which the ions can be regarded as immobile, and thus our description can be applied both to ultracold plasmas with free ions, or to the warm metallic and semiconductor plasmas in which the ions are bound in a crystal lattice.

Usually, quantum plasmas are realized experimentally in the presence of strong laser radiation, and thus in the study of different nonlinear phenomena it is necessary to account also for those associated with the presence of high-frequency radiation. For the simplicity of its quantum description that does not require the relativity considerations, but still accounts for most of the ponderomotive and diffusion effects, we assume that the high-frequency pump wave belongs to the Langmuir branch.

The quantum gas of electrons in an electrostatic electric field is described by the Wigner equation, whose integral form is given by [6,7]

$$\frac{\partial f}{\partial t} + v\frac{\partial f}{\partial x} + \frac{ie}{2\pi\hbar}\int_{-\infty}^{\infty} d\lambda \int_{-\infty}^{\infty} dv'\, e^{im(v-v')\lambda}\left[\phi\left(x+\frac{\lambda\hbar}{2}\right) - \phi\left(x-\frac{\lambda\hbar}{2}\right)\right] f(x,v',t) = 0, \tag{1}$$

where $f(x,v',t)$ is the Wigner distribution function for electrons, $\phi(x,t)$ is the electrostatic potential, while $-e$ and m are the electron charge and mass, respectively. The system is closed by the Poisson equation

$$\frac{\partial^2\phi}{\partial x^2} = \frac{e}{\epsilon_0}\left(\int_{-\infty}^{\infty} dv\, f - n_0\right), \tag{2}$$

where n_0 is the (homogeneous) density of ions. We will restrict ourselves to the regime in which the quantum term can be regarded as small, $\hbar \ll m\Delta_v\Delta_x$, where Δ_x and Δ_v are the typical scales of ϕ and f in the real and velocity spaces, respectively. It should be noted that there exists a lower limit to the characteristic scale Δ_v, that is determined by the weak processes not included at our basic equation (1), but which become dominant at very short scales in velocity space. A working estimate can be obtained e.g. from the Landau collision integral, see p. 36 of the NRL Plasma Formulary [21], yielding $\Delta_v \sim (e^2/\epsilon_0 m v_T)(n\Delta_x)^{1/2}$. For small quantum corrections, expanding $\phi(x \pm \lambda\hbar/2)$ into series around x and keeping only the leading term, the Wigner equation that accounts for

Download English Version:

https://daneshyari.com/en/article/1866429

Download Persian Version:

https://daneshyari.com/article/1866429

Daneshyari.com