Waves and Instabilities in Quantum Plasmas

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Doctoral Thesis
2008

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ISBN: 978-91-7264-508-0
Printed by Print & Media, Umeå 2008-01-28

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Abstract

The study of waves and instabilities in quantum plasmas is of fundamental importance for understanding collective interactions in superdense astrophysical objects, in high intense laser-plasma/solid-matter interactions, in microelectronic devices and metallic nanostructures. In dense quantum plasmas, there are new pressure laws associated with the Fermi-Dirac distribution functions and new quantum forces associated with the quantum Bohm potential and the Bohr magnetization involving electron 1/2 spin. These forces significantly alter the collective behavior of dense quantum plasmas. This thesis contains six papers, considering several novel collective modes and instabilities at quantum scales. In Paper I, we have used the quantum hydrodynamical (QHD) model for studying the one-dimensional dust-acoustic (DA) waves incorporating the Fermi pressure law and the quantum Bohm potential. The latter modifies the DA wave dispersion relation in a collisional plasma. In Paper II, we have calculated the electrostatic potential of a test charge in an unmagnetized electron-ion quantum plasma. It is found that the Debye-Hückel and oscillatory wake potentials strongly depend upon the Fermi energy at quantum scales. The results can be of interest for explaining the charged particle attraction and repulsion in degenerate quantum plasmas, such as those in semiconductor and microelectronic devices. Paper III presents the parametric study of nonlinear electrostatic waves in two-dimensional collisionless quantum dusty plasmas. A reductive perturbation method has been employed to the QHD equations together with the Poisson equation, obtaining the cylindrical Kadomtsev-Petviashvili (CKP) equations and their stationary localized solutions. We have numerically examined the quantum mechanical and geometrical effects on the profiles of nonplanar quantum dust-ion-acoustic (DIA) and DA solitary waves. The role of static as well as mobile (negatively or positively charged) dust particles on the low-frequency electrostatic waves has also been highlighted for metallic nanostructures. Paper IV introduces the nonlinear properties of the ion-sound waves in a dense electron-ion Fermi magnetoplasma.

The computational analysis of the nonlinear system reveals that the Sagdeev-like potential and the ion-sound density excitations are significantly affected by the wave direction cosine and the Mach number at quantum scales. Paper V considers the nonlinear interactions of electrostatic upper-hybrid (UH), ion-cyclotron (IC), lower-hybrid (LH), and Alfvén waves in a quantum magnetoplasma. The nonlinear dispersion relations have been analyzed analytically to obtain the growth rates for both the decay and modulational instabilities involving the dispersive IC, LH, and Alfvén waves. In Paper VI, we have identified a new drift-like dissipative instability in a collisional quantum plasma. The modified unstable drift-like mode can cause cross-field anomalous ion-diffusion at quantum scales.

Keywords: Quantum mechanical effects, dusty plasma, linear and nonlinear waves, instabilities, nonlinear wave interactions, density gradients, and magnetoplasmas, etc.

Papers

The thesis is based on the following papers:

1. Dust acoustic waves in quantum plasmas,

   P. K. Shukla and **S. Ali,**

   Physics of Plasmas **12**, 114502 (2005).

2. Potential distribution around a moving test charge in quantum plasmas,

   S. Ali and P. K. Shukla,

   Physics of Plasmas **13,** 102112 (2006).

3. Parametric study of nonlinear electrostatic waves in two-dimensional quantum dusty plasmas,

   S. Ali, W. M. Moslem, I. Kourakis, and P. K. Shukla,

   New Journal of Physics, in press (2008).

4. Fully nonlinear ion-sound waves in a dense Fermi magnetoplasma,

   S. Ali, W. M. Moslem, P. K. Shukla, and I. Kourakis,

   Physics Letters A **366,** 606 (2007).

5. Nonlinear wave interactions in quantum magnetoplasmas,

   P. K. Shukla, **S. Ali**, L. Stenflo, and M. Marklund,

   Physics of Plasmas **13,** 112111 (2006).

6. Instability of drift-like waves and cross-field charged particle transport in a nonuniform collisional quantum magnetoplasma,

   S. Ali, N. Shukla, and P. K. Shukla,

   Europhysics Letters **78,** 45001 (2007).

Papers by the Author not included in the Thesis

1. Dust acoustic solitary waves in a quantum plasma,

   S. Ali and P. K. Shukla,

   Physics of Plasmas **13**, 022313 (2006).

2. Jeans instability in a plasma with positive-negative charged and neutral dust components,

   S. Ali and P. K. Shukla,

   Physica Scripta **73**, 359 (2006).

3. Dispersion properties of compressional waves in magnetized quantum dusty plasmas,

   S. Ali and P. K. Shukla,

   Physics of Plasmas **13**, 052113 (2006).

4. Dispersive electromagnetic drift modes in nonuniform quantum magnetoplasmas,

   P. K. Shukla and **S. Ali**,

   Physics of Plasmas **13**, 082101 (2006).

5. Quantum dust acoustic double layers,

   W. M. Moslem, P. K. Shukla, **S. Ali**, and R. Schlickeiser,

   Physics of Plasmas **14**, 042107 (2007).

6. Streaming instability in quantum dusty plasmas,

   S. Ali and P. K. Shukla,

   European Physical Journal D **41**, 319 (2007).

7. Solitary, explosive, and periodic solutions of the quantum Zakharov-Kuznetsov equation and its transverse instability,

   W. M. Moslem, **S. Ali**, P. K. Shukla, and X. Y. Tang,

   Physics of Plasmas **14**, 082308 (2007).

8. Three-dimensional electrostatic waves in a nonuniform quantum electron-positron magnetoplasma,

   W. M. Moslem, **S. Ali**, P. K. Shukla, and B. Eliasson,

   Physics Letters A, in press (2008).

9. Linear and nonlinear ion-acoustic waves in an unmagnetized electron-positron-ion quantum plasma,

   S. Ali, W. M. Moslem, P. K. Shukla, and R. Schlickeiser,

   Physics of Plasmas **14**, 082307 (2007).

Chapter 1

Introduction

In this Chapter, we discuss the basic properties and potential applications of dense quantum plasmas as well as present a theoretical background for collective modes and instabilities. We also study the dispersion relations of the most fundamental Langmuir and ion-acoustic waves by taking into account the quantum statistical and diffraction effects.

1.1 Dense Quantum Plasmas

Dense quantum plasma can be composed of electrons, positrons, ions, and charged nanoparticles, is a new emerging and rapidly growing subfield of plasma physics. It is characterized by high-plasma particle number densities and low-temperatures, in contrast to classical plasma which has high-temperatures and low particle number densities. Quantum plasmas are common in different environments, e.g. in superdense astrophysical bodies [1] (i.e. the interior of Jupiter and massive white dwarfs, magnetars, and neutron stars), in intense laser-solid density plasma experiments [2, 3, 4], and in ultrasmall electronic devices (e.g. in microelectronics, semiconductor devices [5], quantum dots, nanowires [6], carbon nanotubes [7], quantum diodes [8], biophotonics [9], ultracold plasmas [10], and microplasmas [11]). More than four decades ago, Pines [12] studied the properties of the high-density and low-temperature quantum plasmas. The latter is gaining momentum [13] in the context of studies of waves, instabilities and nonlinear structures. Quite recently, Glenzer *et al.* [14] have experimentally confirmed the collective x-ray scattering of plasmons in solid-density plasmas.

1.2 Properties of Dense Quantum Plasmas

In quantum plasmas, the Fermi-Dirac statistical distribution is usually employed rather than the widely used Boltzmann-Maxwell distribution in classical plasmas. The typical quantum scales, viz. the time, the length, and the thermal speeds of the charged particles, are quite different from that of classical plasmas.

A one-dimensional zero-temperature Fermi gas obeys the equation of state [13] of the form

$$p_s = \frac{m_s V_{Fs}^2 n_s^3}{3 n_{s0}^2}, \tag{1.1}$$

where m_s is the mass of the species s (s equals e for the electrons, p for the positrons, i for the ions, and d for the dust particles), $V_{Fs} = (2E_{Fs}/m_s)^{1/2}$ is the Fermi speed, E_{Fs} is the Fermi energy, and n_s is the particle number density with an equilibrium value n_{s0}. Equation (1.1) is usually considered in the study of ordinary metals, metal clusters, and nanoparticles, where the electron Fermi temperature is much higher than the room temperature. Due to higher values of the equilibrium number density in quantum plasmas, the plasma frequency $\omega_{ps} = \left(4\pi n_{s0} e^2/m_s\right)^{1/2}$ and the Fermi length $\lambda_{Fs} = V_{Fs}/\omega_{ps} \equiv \left(2k_B T_{Fs}/m_s\right)^{1/2}/\omega_{ps}$ become significantly different from the traditional plasmas. Here e is the magnitude of the electronic charge and k_B is the Boltzmann constant.

The so-called Fermi temperature T_{Fs} can be expressed in terms of equilibrium number density as

$$k_B T_{Fs} = \frac{1}{2} m_s V_{Fs}^2 \equiv E_{Fs} = \left(\frac{\hbar^2}{2m_s}\right)(3\pi^2 n_{s0})^{2/3}, \tag{1.2}$$

where $\hbar$ is the Planck constant divided by 2π. It is noted that when the temperature approaches T_{Fs}, the relevant distribution changes from the Maxwell-Boltzmann to the Fermi-Dirac.

It is well-known [13] that in quantum plasmas, the de Broglie wavelength (viz. $\lambda_{Bs} = \hbar/m_s V_{Fs}$) of the charge carriers is comparable to the dimension of the plasma system. In such a situation, the plasma behaves like a Fermi gas, and the quantum mechanical effects are expected to play a central role in the behavior of charged plasma particles. The de Broglie wavelength roughly represents the spatial extension of Fermion wave function due to quantum uncertainty. In classical plasmas, λ_{Bs} is so small that particles can be assumed as pointlike. As a result, there is no overlapping of waves and no quantum interference. Quantum effects of the particles mainly depends upon their mass. Larger masses will give rise to smaller quantum effects.

It is now reasonable to postulate that the strong electron density correlations start playing a major role when the de Broglie wavelength is equal to or larger than the average interparticle distance $d = n_{e0}^{-1/3}$, that is

$$n_{e0}\lambda_{Be}^3 \geq 1. \tag{1.3}$$

For an opposite condition $n_{e0}\lambda_{Be}^3 < 1$, the plasma particles behave classically.

The quantum coupling parameter Γ_Q, which is defined as the ratio of the interaction energy (E_{int}) to the average kinetic energy ($E_{kin} \equiv E_{Fe}$), reads

$$\Gamma_Q \sim \left(\frac{1}{n_{e0}\lambda_{Fe}^3}\right)^{2/3} \sim \left(\frac{\hbar\omega_{pe}}{E_{Fe}}\right)^2 \equiv \left(\frac{\hbar\omega_{pe}}{k_B T_{Fe}}\right)^2. \tag{1.4}$$

It is interesting to note that Γ_Q is proportional to the square of the ratio between the plasmon energy ($\hbar\omega_{pe}$) and the electron Fermi energy (E_{Fe}). For assuming $\Gamma_Q < 1$, a collisionless quantum plasma (where collective/mean-field effects dominate) can be considered. This is because that all low-energy states are occupied by the Fermions according to the Pauli's exclusion principle in a fully degenerate Fermi gas. When one adds one more Fermion to the gas, occupying a high-energy state, this eventually increases the gas density and reduces the value of Γ_Q. Hence, quantum plasma exhibits collective behavior at large number densities. For $\lambda_{Fe} \to \lambda_{De}$, the quantum coupling parameter tends to the classical coupling parameter (viz. $\Gamma_Q \to \Gamma_C$), where

$$\Gamma_C = \left(\frac{1}{n_{e0}\lambda_{De}^3}\right)^{2/3}. \tag{1.5}$$

For a classical collisionless plasma, Γ_C is small due to large thermal effects, giving rise to weak two-body interactions. Whereas for $\Gamma_C \gtrsim 1$, collisions become important and cannot be neglected.

1.3 Theoretical Background

In fully degenerate quantum plasmas, there are two noteworthy effects. The first one is caused by the quantum force [13] involving the electron tunneling at quantum scales (λ_{Be}) and the second one is due to $1/2$ spin of the electrons and positrons (anti-electrons) in an external magnetic field [15]. The quantum force involving the Bohm potential produces dispersion at quantum scales, while the spin $1/2$ of the electrons give rise to a force that depends on the charged particle magnetic moment $\mu_B = e\hbar/2m_e c$, where c is the speed of light in vacuum. Both effects have important consequences for collective processes in quantum plasmas.

Important quantum effects in compressible quantum fluids–for example, the electron tunneling through a potential barrier in a semiconductor–near thermal equilibrium in the high-frequency limit have been described with the quantum hydrodynamical (QHD) equations [16], which have the same form as the classical hydrodynamical equations (the Euler equations for gas dynamics). Later, the QHD equations have been expressed [17] in the framework of the quantum Liouville equation, highlighting the importance of quantum force $-\boldsymbol{\nabla}\varphi_B$, where $\varphi_B = -(\hbar^2/2m_e\sqrt{n_e})\nabla^2\sqrt{n_e}$ is the quantum Bohm potential. The latter appropriately describes negative differential resistance and resonant tunneling in semiconductor physics [16]. New scaling of the Child-Langmuir (CL) law was presented by Ang and co-workers [8] in the quantum regime. They found that the classical value of the CL law is increased by a larger factor due to the electron tunneling through the space-charge potential and the electron exchange-correlation interaction, can be important when the applied gap voltage and the gap spacing are, respectively, on the Hartree energy level, and at nanometer scales.

The quantum transport models similar to the QHD model have also been employed in superfluidity [18], superconductivity [19], and in metal clusters and nanoparticles, where they are referred to as non-stationary Thomas-Fermi (TF) models. Haas *et al.* [20] introduced a quantum multistream model using the nonlinear Schrödinger-Poisson system. They derived the dispersion relations for one- and two-stream plasma instabilities, reporting that the two-stream instability is enhanced for small quantum effects in a plasma. A comparative study of instabilities was presented by Anderson *et al.* [21], by using the Wigner-Moyal representation [22]. They showed that a Landau-like damping suppresses the instabilities in one- and two-stream type while considering the statistical aspects of the multistream quantum plasma. Later, this work was extended to study the stability of small amplitude electrostatic waves in a three-stream quantum plasma [23]. Recently, the linear and nonlinear properties of the quantum ion-acoustic (QIA) waves have been investigated [24] in a quantum plasma, by using one-dimensional QHD equations for inertialess electrons and mobile ions. It was found that the quantum Bohm potential modifies the linear wave dispersion and affects strongly the QIA solitary waves. Luque *et al.* [25] solved the Wigner-Poisson system and predicted the existence of the quantum correlated electron holes in an unmagnetized quantum plasma. Very recently, Misra *et al.* [26] investigated the electron-acoustic solitary waves in a nonplanar quantum plasma, whose constituents are two groups of electrons: the inertial cold electrons and inertialess hot electrons as well as the stationary ions. They observed that the presence of cold electrons plays a dominant role in the formation of both bright and dark solitons. Sahu and Roychoudhury [27] studied spherical and cylindrical QIA waves in a two-component unmagnetized plasma and examined geometric and quantum effects on the soliton pulses. They also extended their work [28] for QIA shocks in planar as well as nonplanar geometries.

Laboratory and dense astrophysical quantum plasmas can be confined by an external magnetic field and may also have density gradients. In this context, a three-dimensional QHD model has been developed [29] for dense magnetized plasmas by establishing the conditions for an equilibrium in the ideal quantum magnetohydrodynamics (MHD). Marklund and Brodin [15] obtained a quantum MHD model incorporating the electron spin effect, but ignoring the strong density fluctuation effects of the electrons in spin quantum magnetoplasmas [30]. They found that the electron $1/2$ spin effect modifies the spectra of the fast and slow MHD modes. Furthermore, Ali *et al.* [31] presented a fully nonlinear theory for ion-sound waves in a dense Fermi magnetoplasma. Shukla and Stenflo [32, 33] discussed the dispersive properties of shear Alfvén waves in a uniform quantum magnetoplasma, taking into account the strong electron and positron correlations. The shear Alfvén mode acquires additional dispersion due to quantum corrections at quantum scales. Later, new electrostatic and electromagnetic drift modes [34, 35] have been investigated in the presence of the density gradient in a nonuniform quantum magnetoplasma. A new drift-like dissipative instability has also been found [36] in quantum plasmas incorporating the density gradients and the electron-neutral collisions.

Nonlinear wave-wave and wave-particle interactions in quantum plasmas are of fundamental importance because of dispersive nature of electrostatic waves, e.g. plasmons and ion oscillons at quantum scales. In this context, it is quite practical to investigate the parametric interactions between high- and low-frequency oscillations. Garcia *et al.* [37] have derived the modified Zakharov equations due to the nonlinear coupling between the modified Langmuir and QIA waves and showed the modification of the growth rates of the decay and modulational instabilities. The influence of a background random phase on the modulational instability of partially incoherent Langmuir waves was also examined [38]. Shukla and Stenflo [39] studied the nonlinear interaction between a large amplitude electromagnetic wave and low-frequency electron and ion plasma oscillations. They found new classes of three-wave decay and modulational instabilities. This work was later extended [40] to consider the nonlinear interactions of upper-hybrid waves (UH), ion-cyclotron waves (IC), lower-hybrid waves (LH), and Alfvén waves in quantum magnetoplasmas. Some efforts [41, 42] have been made for studying the interaction of charge particles with plasma waves in classical plasmas. However, more recently, the electrostatic potential of a slowly moving test charge is computed [43] in the electron-hole Fermi plasma using the dielectric constant for longitudinal perturbations. It was found that the near and far-field potentials are controlled by a quantum scalelength $\left(K_{FT} = \sqrt{3}\omega_{ps}/V_{Fs}\right)$ that depends on the Fermi energy. The study has further been extended [44] to demonstrate the existence of the wake-potential due to resonant interaction between the test charge and plasma oscillations in an unmagnetized electron-ion quantum plasma.

The presence of charged dust impurities in a classical three-component plasmas leads to generate new modes such as the dust-acoustic (DA) [45] and dust-ion-acoustic (DIA) [46] waves, which have been observed in many laboratory experiments (e.g. Ref. [47] and references therein). Dust impurities exist in the quantum plasma, forming a quantum dusty plasma, for instance, microelectronic devices and metallic nanostrctures are usually contaminated by the presence of highly charged dust impurities. The latter also appear in astrophysics (e.g. supernova environments) and are likely to be found in ultraintense laser-solid material plasma (clusters) interaction experiments [4]. Due to the small mass of the electrons compared to ions and dust particulates, the quantum behavior of the electrons is reached more easily.

A large number of collective modes and instabilities have been studied [48, 49, 50, 51, 52] in a dust-contaminated quantum plasma. The collective modes are stable in the equilibrium plasma and become unstable in a non-equilibrium plasma due to an availability of free energy sources. The amplitudes of the collective modes grow or damp exponentially with respect to time, depending on the signature of the imaginary wave frequency. If the signature is positive, the waves will grow, and otherwise it will damp. The linear and nonlinear properties [53, 54] of DA waves have recently been investigated in an unmagnetized quantum electron-ion-dust plasma. It is noted that the dispersive properties and nonlinear propagation characteristics of the DA waves are significantly modified due to the Fermi statistics and quantum diffraction effects. Moslem *et al.* [55] expressed the DA double layers in quantum dusty plasmas. Furthermore, Misra *et al.* [56] examined the amplitude modulations of the DA and IA waves. They demonstrated the existence of the modulational instability and envelope solitons in quantum plasmas. Quite recently, Khan and Mushtaq [57] investigated the linear and nonlinear properties of the DIA waves in an unmagnetized quantum dusty plasma.

1.4 Collective Modes in Quantum Plasmas

There are numerous collective effects involving the quantum corrections studied in collisionless quantum plasmas [15, 25, 37, 38, 43, 50, 58, 59]. They include studies of the Debye screening in quantum plasmas, Langmuir and ion waves, quantum surface waves, quantum drift waves, quantum magnetohydrodynamic waves, quantum dark solitons and vortices, and quantum Bernstein-Greene-Kruskal equilibria, etc. The most fundamental of these waves are the Langmuir and ion-acoustic waves. The linear dispersive properties of the latter can be studied in a collisionless unmagnetized quantum plasma.

By assuming the electrons as mobile having stationary ions in the background and employing the quantum hydrodynamical equations, we obtain the dispersion relation ($\omega - k$ relation) of the Langmuir waves

$$\omega^2 = \omega_{pe}^2 + k^2 V_{Fe}^2 + \frac{\hbar^2 k^4}{4m_e^2}, \tag{1.6}$$

where $\omega_{pe} = \left(4\pi n_{e0} e^2/m_e\right)^{1/2}$ and $V_{Fe} = (2k_B T_{Fe}/m_e)^{1/2}$. It is noted that the wave frequency of the Langmuir waves is significantly modified with quantum corrections.

For quantum ion-acoustic waves, the electrons are treated as inertialess and ions as mobile.

Using the approximations kV_{Fi}, $\hbar k^2/m_i \ll \omega \ll kV_{Fe}$ and $kV_{Fe} > \hbar k^2/m_e$, we obtain

$$\omega^2 = \frac{k^2 C_s^2 \left(1 + H_e^2 k^2 \lambda_{Fe}^2/4\right)}{1 + k^2 \lambda_{Fe}^2 \left(1 + H_e^2 k^2 \lambda_{Fe}^2/4\right)}, \tag{1.7}$$

where $C_s = (2k_B T_{Fe}/m_i)^{1/2}$ is the ion-acoustic speed, $\lambda_{Fe} = \left(2k_B T_{Fe}/4\pi n_{e0} e^2\right)^{1/2}$ is the electron Fermi length, and $H_e = (\hbar\omega_{pe}/2k_B T_{Fe})$ is the quantum parameter. For $H_e \to 0$, one can reproduce the usual dispersion relation of classical physics.

1.5 Motivation/Applications

Quantum plasmas have attracted a noticeable interest of the plasma community in the last few years [13, 24, 30, 36, 43, 44, 50, 51, 54] and gained momentum [13] in the context of studies of waves, instabilities and nonlinear structures. The main reason of attraction is, the new development in manufacturing electronics and nanoscale technology [60], the discovery of the ultracold plasmas [10, 61], and the experimental demonstration [62] of quantum plasma oscillations in Rydberg systems.

Strongly coupled quantum electron plasmas occur in an ordinary metals and metallic nanostructures (metal clusters, nanoparticles, and thin metal films) composed of a small number of atoms (typically ten to hundred thousands). For understanding the electron dynamics in metallic nanostructures, the ultrafast (femto and attosecond) laser sources can be used. Metallic nanostructures constitute an ideal arena for studying the dynamical properties of quantum plasmas. Quantum behavior also exists in semiconductors containing electrons and holes. Although the number densities of the latter are much smaller than in metals, the great degree of miniaturization of electronic components is such that the de Broglie wavelength of the charge carriers can be comparable to the spatial variation of the doping profiles. Hence, a typical quantum effect, such as tunneling, is expected to play a role in the behavior of electronic components to be constructed in the future. However, the issues related to resonant tunneling and negative differential resistance [16] can be overcome appropriately by the quantum Bohm potential.

Quantum mechanical effects have also been recognized in superdense astrophysical systems [1], for example, the interior of Jupiter and white dwarfs, neutron stars and supernova, where the density is ten order of magnitudes larger than that of ordinary solids. Likewise, the importance of quantum effects has been experimentally demonstrated [14] in inertial confinement plasmas. It is expected that ultraintense laser-solid matter interactions will also reveal new aspects of collective features (e.g. stimulated Raman and Brillouin scatterings of light off plasmons and ion oscillations) at nanometer scales. Furthermore, quantum mechanical effects play a significant role in the nonlinear quantum optics [63, 64].

Thus, recognizing the great overlap in the physics of different environments and their applications, motivates us to study dense quantum plasmas.

1.6 Outline of Thesis

This thesis is organized as follows: In Chapter 2, we study the Schrödinger-Poisson and the Wigner-Poisson models for describing the hydrodynamical and statistical behaviors of the plasma particles in dense quantum plasmas. Chapter 3 contains summaries of the papers. Some conclusions and future perspectives are discussed in Chapter 4. In Paper I, a linear dispersion relation of the DA wave is derived in a collisional quantum dusty plasma incorporating the Fermi statistics and quantum tunneling effects. Paper II deals with the propagation of a test charge along the z-axis in an electron-ion quantum plasma. It is numerically found that the Debye-Hückel and wake potentials are significantly modified due to the Fermi energy. Paper III presents the parametric study of nonlinear electrostatic waves in a collisionless unmagnetized quantum dusty plasma. It has been noted that the profiles of the DIA and DA solitary waves are strongly affected by the presence of quantum mechanical effects, the dust charge polarity, and the nonplanar geometry. In paper IV, the nonlinear properties of the ion-sound waves are studied in a dense electron-ion Fermi magnetoplasma. Paper V is devoted to the nonlinear couplings between electrostatic upper-hybrid (UH), ion-cyclotron (IC), lower-hybrid (LH), and Alfvén waves in a quantum magnetoplasma. The nonlinear dispersion relations are further analyzed analytically for the growth rates of the decay and modulational instabilities involving dispersive IC, LH, and Alfvén waves. Paper VI introduces a new drift-like dissipative instability in a collisional quantum plasma. It is shown that the modified unstable drift-like mode causes a cross-field anomalous ion-diffusion at quantum scales.

In the next Chapter, we study the Schrödinger-Poisson and the Wigner-Poisson models.

Chapter 2

Governing Equations

In this Chapter, we study the Schrödinger-Poisson and the Wigner-Poisson models for describing the hydrodynamical and statistical behaviors of the plasma particles in dense quantum plasmas.

The modeling of quantum plasmas is essentially based upon the well-known mathematical approaches, the Schrödinger-Poisson, and the Wigner-Poisson, which have been widely used to study the hydrodynamical and statistical behaviors of the plasma particles at quantum scales. These approaches are the quantum analogues of the fluid and kinetic models in classical plasma physics. In this context, Manfredi [13] has briefly demonstrated all the approaches in an unmagnetized collisionless electrostatic quantum plasma.

2.1 Schrödinger-Poisson System

One of the most basic quantum effect is that particles are described by wave functions rather than classical point particles. In this context, we first consider a one-dimensional quantum plasma [13] in which the electrons are described by the statistical mixture of N pure states ψ_α, obeying N independent Schrödinger equations, coupled through the Poisson equation

$$i\hbar\frac{\partial\psi_\alpha}{\partial t} = -\frac{\hbar^2}{2m_e}\frac{\partial^2\psi_\alpha}{\partial x^2} - e\varphi\psi_\alpha + W_{eff}\psi_\alpha, \tag{2.1}$$

$$\frac{\partial^2\varphi}{\partial x^2} = 4\pi e\left(\sum_{\alpha=1}^{N}|\psi_\alpha|^2 - n_0\right), \tag{2.2}$$

where $\alpha = 1, 2, ..N$ numbers the electrons, φ is the electrostatic potential, $W_{eff} = m_e V_{Fe}^2 |\psi_\alpha|^4 / 2n_{\alpha 0}^2$ is the effective potential, m_e is the mass of the electron, and e is the magnitude of the electronic charge. The electrons are globally neutralized by the fixed ion background density n_0.

We now introduce the real amplitude A_α and the real phase S_α associated to the pure state ψ_α as

$$\psi_\alpha = A_\alpha \exp\left(\frac{iS_\alpha}{\hbar}\right), \tag{2.3}$$

where

$$A_\alpha = \sqrt{n_\alpha} \quad \text{and} \quad m_e U_\alpha = \frac{\partial S_\alpha}{\partial x}.$$

Inserting Eq. (2.3) into Eqs. (2.1) and (2.2) and separating the real and imaginary parts of the equations, we obtain the continuity, momentum, and Poisson equations:

$$\frac{\partial n_\alpha}{\partial t} + \frac{\partial}{\partial x}(n_\alpha U_\alpha) = 0, \tag{2.4}$$

$$\left(\frac{\partial U_\alpha}{\partial t} + U_\alpha \frac{\partial U_\alpha}{\partial x}\right) = \frac{e}{m_e}\frac{\partial \varphi}{\partial x} - \frac{1}{m_e n_\alpha}\frac{\partial p_\alpha}{\partial x} + \frac{\hbar^2}{2m_e^2}\frac{\partial}{\partial x}\left(\frac{\partial^2\left(\sqrt{n_\alpha}\right)/\partial x^2}{\sqrt{n_\alpha}}\right), \tag{2.5}$$

and

$$\frac{\partial^2 \varphi}{\partial x^2} = 4\pi e\left(\sum_{\alpha=1}^{N} n_\alpha - n_0\right). \tag{2.6}$$

The second term in the right-hand side of Eq. (2.5) contains a Fermi pressure $p_\alpha = m_e V_{Fe}^2 n_\alpha^3 / 3n_{\alpha 0}^2$, describing the quantum statistical effects. Basically, it represents the fermionic behavior of the plasma particles and plays a significant role in the study of ordinary metals, metal clusters, and nanoparticles, where the electron Fermi temperature is much higher than the room temperature. The other most common choice for p_α can be the isothermal pressure law ($p_\alpha = n_\alpha k_B T_\alpha$), where T_α is the temperature. However, the last term of Eq. (2.5) represents the quantum force involving the quantum Bohm potential, which is due to the effect of wave function spreading, giving rise to a dispersive-like term. The quantum Bohm potential has recently received much attention for resonant tunneling phenomena and negative differential resistance in semiconductor physics [16]. Equations (2.4)-(2.6) represent a quantum hydrodynamical (QHD) model, describing essentially the transport of charge density, momentum including the Bohm potential, and energy in a charged particle system interacting through a self-consistent electrostatic potential. It is noted that the QHD model is a macroscopic model, dealing with the behavior of macroscopic quantities like density and current. Equations (2.4) and (2.5) can be derived by considering the moments of the Wigner-Poisson system in velocity space in the long wavelength limit, i.e. $k\lambda_{Fe} \ll 1$, where k is the wave number and λ_{Fe} is the Fermi wavelength.

In order to consider one stream case, we take $\alpha = 1$, (a single pure quantum state) and write $n_1 = n$ and $U_1 = U$ in Eqs. (2.4)-(2.6). For an equilibrium state, we have $n = n_0$ and $U = U_0$ at $\varphi_0 = 0$. Using the Fourier decomposition of the perturbed quantities of Eqs. (2.4)-(2.6), we obtain the dielectric constant for the quantum plasmas

$$\varepsilon(k, \omega) = 1 - \frac{\omega_{pe}^2}{(\omega - kU_0)^2 - k^2V_{Fe}^2 - \hbar^2k^4/4m_e^2}, \tag{2.7}$$

where ω is the angular wave frequency, U_0 is the equilibrium velocity of the stream (a constant drift relative to the stationary ion background), and the term kU_0 represents a Doppler shift. ω_{pe} is the plasma frequency and V_{Fe} is the Fermi speed.

Similarly, for two streams propagating with the velocities U_{01} and U_{02}, with the background densities n_{01} and n_{02}, the dielectric constant can be expressed as

$$\varepsilon(k, \omega) = 1 - \frac{\omega_{p1}^2}{(\omega + kU_{01})^2 - k^2V_{Fe}^2 - \hbar^2k^4/4m_e^2} - \frac{\omega_{p2}^2}{(\omega - kU_{02})^2 - k^2V_{Fe}^2 - \hbar^2k^4/4m_e^2}, \tag{2.8}$$

where $\omega_{p1} = \left(4\pi n_{01}e^2/m_e\right)^{1/2}$ and $\omega_{p2} = \left(4\pi n_{02}e^2/m_e\right)^{1/2}$. Equation (2.8) gives a two stream instability [65] in dense quantum plasmas.

2.2 Wigner-Poisson System

In order to take the statistical effects into account, we now consider the Wigner distribution function, which is a function of the phase space variables (x, V) and time t, as [13]

$$f_e(x, V,\ t) = \frac{m_e}{2\pi\hbar}\sum_{\alpha=1}^{N} p_\alpha \int_{-\infty}^{\infty} \exp\left(\frac{im_eV\lambda}{\hbar}\right)\psi_\alpha^*\left(x + \frac{\lambda}{2},\ t\right)\psi_\alpha\left(x - \frac{\lambda}{2},\ t\right)d\lambda. \tag{2.9}$$

Notice that the one-particle Wigner distribution function actually represents N-particle system, $\psi_\alpha(x,t)$ denotes the N single-particle wave functions each characterized by a probability p_α satisfying $\sum_{\alpha=1}^{N} p_\alpha = 1$. The Wigner function is not a true probability density, as it can take negative values. However, it can be employed for calculating the averages in the similar way as in classical statistical mechanics. For example, the expectation value of a quantity $A(x,V)$ can be expressed as

$$\langle A\rangle = \frac{\int\int f_e(x,\,V)\,A(x,\,V)\,dxdV}{\int\int f_e(x,\,V)\,dxdV}.$$

Similarly, the number density in terms of the Wigner distribution function is given by

$$n_e(x,t) = \int_{-\infty}^{\infty} f_e(x,V,\,t)\,dV {=} \sum_{\alpha=1}^{N} p_\alpha\,|\psi_\alpha|^2 .$$

The Wigner distribution function obeys the following one-dimensional evolution equation:

$$\frac{\partial f_e}{\partial t} {+} V\frac{\partial f_e}{\partial x} {+} \frac{em_e}{2\pi i\hbar^2}\int\int d\lambda\, d\acute{V}\,\exp\left(\frac{im_e\left(V-\acute{V}\right)\lambda}{\hbar}\right)\left[\varphi\left(x+\frac{\lambda}{2}\right)-\varphi\left(x-\frac{\lambda}{2}\right)\right] f_e\left(x,\acute{V},\,t\right) = 0, \tag{2.10}$$

where $\varphi(x)$ is the self-consistent electrostatic potential.

Differentiating (2.9) with respect to t and by using the Schrödinger equation and separating the resultant equation into kinetic and potential terms as

$$\frac{\partial f_e}{\partial t} = K + U, \tag{2.11}$$

with

$$K = \frac{1}{4\pi i}\sum_{\alpha=1}^{N} p_\alpha \int_{-\infty}^{\infty}\exp\left(\frac{im_eV\lambda}{\hbar}\right)\left[\psi_\alpha(-)\frac{\partial^2}{\partial x^2}\psi_\alpha^*(+) - \psi_\alpha^*(+)\frac{\partial^2}{\partial x^2}\psi_\alpha(-)\right]d\lambda, \tag{2.12}$$

and

$$U = \frac{em_e}{2\pi i\hbar^2}\sum_{\alpha=1}^{N} p_\alpha \int_{-\infty}^{\infty}\exp\left(\frac{im_eV\lambda}{\hbar}\right)\left[\varphi(+)-\varphi(-)\right]\psi_\alpha^*(+)\,\psi_\alpha(-)\,d\lambda. \tag{2.13}$$

Here $\psi_\alpha(-) = \psi_\alpha(x-\lambda/2,\ t)$ and $\psi_\alpha^*(+) = \psi_\alpha^*(x+\lambda/2,\ t)$. Now by comparing (2.10) and (2.11), we obtain

$$K = -V\frac{\partial f_e}{\partial x}, \tag{2.14}$$

and

$$U = -\frac{em_e}{2\pi i\hbar^2}\int\int d\lambda\, d\acute{V}\ \exp\left(\frac{im_e\left(V-\acute{V}\right)\lambda}{\hbar}\right)\left[\varphi\left(+\right)-\varphi\left(-\right)\right]f_e\left(x,\acute{V},t\right). \tag{2.15}$$

The Wigner equation (2.10) can be obtained by inserting the Wigner function in the right hand side of Eqs. (2.14) and (2.15) and showing the resulting equations to be the same as (2.12) and (2.13).

Now we assume $s = m_e\lambda/\hbar$ in (2.10) and use the Taylor expansion of φ upto third order around x for small "$\hbar$", we finally arrive at

$$\frac{\partial f_e}{\partial t} + V\frac{\partial f_e}{\partial x} - \frac{e}{m_e}\frac{\partial\varphi}{\partial x}\frac{\partial f_e}{\partial V} \approx -\frac{e\hbar^2}{24m_e^3}\frac{\partial^3\varphi}{\partial x^3}\frac{\partial^3 f_e}{\partial V^3} + O(\hbar^4). \tag{2.16}$$

The right-hand side of (2.16) is due to the strong density correlations. It is now easy to see that, in the limit $\hbar \to 0$, one recovers the familiar Vlasov equation for a classical collisionless plasma.

The Wigner equation can be coupled with the Poisson equation through the electrostatic potential

$$\frac{\partial^2\varphi}{\partial x^2} = 4\pi e\left(\int f_e dV - n_0\right). \tag{2.17}$$

Equation (2.17) shows that the ions form a motionless neutralizing background with a uniform number density n_0. This model is restricted to a one-dimensional case, however, one can easily generalize it for a three-dimensional case.

Chapter 3

Summaries of the Papers

This thesis contains investigations of numerous novel features of waves and associated instabilities in dense quantum plasmas. It consists of six research publications, which are briefly summarized below:

3.1 Paper I

This paper presents the quantum hydrodynamical (QHD) equations for a collisional unmagnetized quantum plasma, whose constituents are the inertialess electrons and ions, as well as mobile negatively charged dust particles. A dispersion relation for an extremely low-phase speed electrostatic dust acoustic (DA) waves is obtained incorporating the dust-neutral collisions at quantum scales. It has been noted that the DA wave is modified by the Fermi statistics and the strong density correlations of the plasma species. The study can be helpful for diagnostics of charged dust impurities in microelectronics and in ultraintegrated devices.

3.2 Paper II

In this paper, we calculate the electrostatic potential of a test charge propagating with a constant velocity along the z-axis in an electron-ion quantum plasma. By employing the QHD model and Poisson equation, a Debye-Hückel potential for a slowly moving test charge is derived as well as an oscillatory wake potential due to resonant interaction of a test charge and quantum ion-acoustic oscillations. Numerical investigation exhibits that the profiles of the Debye- and wake-potentials are modified for the electron quantum statistics and quantum diffraction effects. Our results have applications to charged particle repulsion and attraction in degenerate quantum plasmas, such as those in micromechanical and ultrasmall electronic devices, as well as in dense astrophysical environments and in laser and microplasmas.

3.3 Paper III

We investigate the nonlinear properties of quantum DIA and DA waves in a very dense quantum nonplanar dusty plasma, composed of electrons, ions, and charged dust particles. By employing the reductive perturbation method to the QHD and the Poisson equations, we derive the two-dimensional CKP-type equations and their stationary localized solutions. The computational studies have been performed to examine the quantum mechanical effects on the electrostatic potential excitations, in terms of the radial and polar angle coordinates, by varying relevant physical parameters. It is found that the amplitudes and widths of the nonplanar quantum DIA and DA waves are significantly affected by the quantum tunneling effect. In particular, addition of dust to a quantum plasma is seen to modify the charge balance (via an associated electron density depletion, for negative dust, or vice versa), and thus affects the propagation characteristics (including a strong modification of the phase speed) of localized (dust-) ion-acoustic excitations. In the case of the low-frequency dust-acoustic waves this effect is even stronger, since the actual form of potential solitary waves, in fact, depends on the dust charge polarity (positive/negative) itself (allowing for positive/negative potential forms, respectively). These results should be helpful for understanding the nonlinear electrostatic waves in metallic nanostructures involving charged particles in nanomaterials.

3.4 Paper IV

This paper considers the nonlinear ion-sound waves in a dense electron-ion Fermi magneto-plasma. The dynamics of the ion fluid is governed by the ion continuity and momentum equations, while the electrons are assumed inertialess. An energy balance equation involving a new Sagdeev-like potential is calculated accounting for the quantum statistical effects. The numerical investigations of the nonlinear system reveal that the Sagdeev-like potential and the ion-sound density excitations are significantly affected by the wave direction cosine and the Mach number at quantum scales.

3.5 Paper V

This paper introduces the study of nonlinear couplings between electrostatic upper-hybrid (UH), ion-cyclotron (IC), lower-hybrid (LH), and Alfvén waves in a quantum magnetoplasma. By using a one-dimensional quantum magnetohydrodynamical model, we derive the governing nonlinear equations, which are then Fourier analyzed to obtain nonlinear dispersion relations. The latter contain quantum corrections arising from the electron tunneling at quantum scales. The dispersion relations are further analyzed analytically for the growth rates of the decay and modulational instabilities involving dispersive IC, LH, and Alfvén waves. Since the frequencies of these waves are significantly modified due to the quantum corrections, the growth rates are accordingly affected in a quantum magnetoplasma.

3.6 Paper VI

We consider a nonuniform partially ionized quantum magnetoplasma containing electrons, ions, and stationary neutrals. The quasineutrality condition at equilibrium $n_{i0}(x) = n_{e0}(x)$ gives the density variations of the electrons and ions along the x-axis. A novel dispersion relation is derived for the low-frequency (in comparison with the ion gyrofrequency) electrostatic drift-like wave in the presence of electron-neutral collisions. It is found that the drift-like dissipative instability is proportional to $k_y^2\rho_s^2$ (where ρ_s is the ion-sound gyroradius), showing that the finite ion polarization drift is essential for this instability. Physically, the instability arises because the plasma density fluctuations cannot keep in phase with the drift wave potential due to a non-Boltzmann electron density distribution arising from electron-neutral collisions and the ion polarization drift that separates the charges. Thus, the energy stored in the equilibrium density gradient is channelled to drift waves via collisions. Further, the cross-field ion diffusion in the presence of the unstable drift modes is also investigated.

Chapter 4

Conclusions and Future Perspectives

The aim of the present thesis is to investigate the collective modes and instabilities in dense quantum plasmas by using the quantum hydrodynamical equations. The collective behavior of dense quantum plasmas is significantly affected by the new Fermi pressure law associated with the Fermi-Dirac distribution function and a new quantum force associated with the quantum Bohm potential. We conclude the main results of the thesis as follows:

- We have discussed the basic properties and potential applications of dense quantum plasmas. It is found that the quantum scales, such as the time, the speed, and the length, are completely different from that of classical plasma scales. We have also presented a theoretical background for the waves and instabilities as well as studied the dispersion relations of the Langmuir and ion-acoustic waves at quantum scales.

- We have described both macroscopic and microscopic approaches, namely, the Schrödinger-Poisson and the Wigner-Poisson for modeling the unmagnetized dense quantum plasmas.

- We have derived a linear dispersion relation for the DA wave in a collisional quantum dusty plasma, which has been significantly modified from that of traditional classical dusty plasma. This model may be helpful for diagnostics of charged dust impurities in microelectronics.

- We have presented the analytical and numerical studies of the electrostatic potential due to a test charge propagating with a constant velocity through an electron-ion quantum plasma. It is noticed that the electrostatic potential depends on the dielectric constant of the IA waves containing the quantum mechanical effects. Likewise, the Debye-Hückel and oscillatory wake potentials have been studied at quantum scales both analytically and numerically. Our results are of fundamental interest in the context of charged particle repulsion and attraction in degenerate quantum plasmas, such as those in micromechanical and ultrasmall electronic devices, as well as dense astrophysical environments and in laser and microplasmas.

- We have investigated the nonlinear properties of nonplanar quantum DIA and DA waves in an unmagnetized, collissionless quantum dusty plasma by using the QHD equations together with the Poisson equation. By means of computational investigations, the effects due to quantum tunneling, quantum statistics, dust charge polarity, and nonplanar geometry, have been examined on the profiles of the quantum DIA and DA solitary waves. The main objective is to highlight the role of static as well as mobile (negatively or positively charged) dust impurities on the low-frequency electrostatic waves propagating in a quantum dusty plasma.

- We have considered the nonlinear IA waves propagating obliquely to an external magnetic field in a collisionless quantum electron-ion magnetoplasma. For this purpose, we have obtained a Sagdeev-like pseudo-potential by employing the QHD equations. It is found that only subsonic IA solitary waves may exist. Numerically, we have observed the effects of the quantum statistics, the wave directional cosine, and the Mach number on the density profiles of the nonlinear IA waves.

- We have presented the nonlinear dispersion relations of the UH, IC, LH, and Alfvén waves in a collisionless magnetized quantum plasma. For a classical limit $\hbar \to 0$, the dispersion relations of the traditional plasma have been retrieved. By using the slow and fast time-scale theory, we have coupled the high frequency UH pump waves with the low frequency IC, LH, and Alfvén waves. In each case, the lower and upper sidebands are produced with different frequencies and wavenumbers exhibiting a dispersion relation of parametric instability. The growth rates have been derived due to three wave decay interaction while assuming the lower sideband to be resonant and the upper one off-resonant. Similarly, for modulational instabilities both the sidebands have been considered to be resonant. Finally, we have noted that the growth rates are strongly influenced by the quantum tunneling effect.

- We have introduced a new drift-like dissipative instability in a partially ionized nonuniform quantum magnetoplasma by taking into account the density gradients and the electron-neutral collisional effects. The quantum diffraction effect associated with the strong electron density correlation has modified the drift wave frequency and growth rate. We have examined that enhanced drift wave turbulence causes the cross-field ion-diffusion. The present results might be useful in understanding the origin of low-frequency drift modes and associated cross-field ion transport in nonuniform collisional quantum magnetoplasmas, such as those in superdense astrophysical bodies (e.g. the interior of neutron stars and massive white dwarfs), as well as in forthcoming intense laser-solid density plasma experiments and in microplasmas.

Finally, we would like to include some suggestions for future work. We have studied the nonlinear structures and instabilities in a nonrelativistic dense quantum plasma, it is recommended that a natural extension of our work is to consider the relativistic case in dense quantum plasmas. Similarly, we have presented the analytical and numerical study of the electrostatic potential due to a single test charge. One can extend the work for energy loss in dense quantum plasmas. There is also a possibility for extension, considering the strong magnetic field and spin 1/2 effects. The waves and instabilities caused by the number density, velocity, and magnetic field gradients also need to be investigated in a nonuniform magnetized quantum plasma.

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Acknowledgements

First and foremost, I want to express my deepest gratitude to my respectable supervisor and teacher **Professor Padma Kant Shukla** for his invaluable guidance and excellent supervision. I have greatly benefited from his knowledge and expertise in plasma physics. I am extremely thankful to him for providing me a supportive environment and research facilities during my stay at the Ruhr-Universität Bochum, Germany.

Secondly, my heartfelt gratitude goes to **Professor Mattias Marklund** my co-supervisor, for his fruitful discussions and suggestions enabled me to complete this work. I would like to thank him for his hospitality during my visit to Umeå University, Sweden.

I am extremely obliged to Professor L. Stenflo and Professor G. Brodin for their assistance, advice, and moral support. I would also like to thank Dr. B. Eliasson, Dr. I. Kourakis, Dr. M. Diekmann, Dr. W. M. Moslem, and Dr. M. Lazar for meaningful discussions, cooperation and help whenever I needed in the research work. The suggestions from Dr. F. Haas are also gratefully appreciated.

I acknowledge the financial support provided by the Deutscher Akademischer Austausch Dienst (DAAD) Bonn, Germany.

Last but not the least, I wish to record my deepest obligations to my parents, my brothers and sisters, my wife, and children for their sustained love and cooperation.