Int. J. Nonlinear Anal. Appl. 16 (2025) 1, 51–57
ISSN: 2008-6822 (electronic)
http://dx.doi.org/10.22075/ijnaa.2023.30599.4439

Investigating magnetoacoustic waves in a semiconductor plasma

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(Communicated by Haydar Akca)

Abstract

In this research, the scattering properties of magneto-acoustic waves in plasma and the presence of Coulomb exchange effects and quantum effects have been investigated. A set of quantum fluid equations and Maxwell's equations (Consisting of Bohm potential, Fermi pressure, and exchange correlation) have been used to obtain a generalized dispersion relation. In semiconductor quantum plasma, scattering effects are due to charge separation between electrons and holes, quantum repulsion, nonlinearities due to large amplitude electrostatic potential, quantum degeneracy pressure, and exchange-correlation interaction. Therefore results show that the quantum corrections lead to changes in the scattering relationship and scattering properties of wave modes. In addition, it was shown that the corrections related to thermal effects are more important than quantum and magnetic field effects, and the results show that quantum effects are negligible compared to thermal and magnetic effects, and the contribution of exchange-correlation interaction also becomes significant with the increase of the external magnetic field. These results may be necessary for very small electronic devices or solid-density plasmas and the understanding of numerous collective phenomena in quantum plasmas.

Keywords: Magneto-acoustic wave, QHD model, quantum plasma, semiconductor plasma
2020 MSC: 82D10, 76E25

1 Introduction

Since the field of quantum plasma is considered one of the most widely used scientific fields, many researchers are researching and studying it today. For the first time in 1960, the discussion about quantum plasma was raised by Pence in physical regimes with high density and low temperature. Studies were also conducted in the last decade in the field of quantum semiconductor plasma, but the research related to understanding the behavior and characteristics of waves in these plasmas is limited. Among the models used to study the properties of diffusion in quantum plasma systems is the quantum hydrodynamic model [27, 28]. Linear characteristics of longitudinal electro-kinetic waves in quantum semiconductor plasma have been investigated and analyzed using this model [21]. In dense quantum plasma systems that contain a large number of electrons, the interaction between electrons can be separated into two parts, one of which is caused by the electrostatic potential (Hartree's theorem), and the other is known as the electron

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Received: May 2023 *Accepted:* November 2023

exchange-correlation. The electron exchange-correlation is a complex function of electron density and is obtained through density approximation [8, 11]. Jung et al. have investigated the effect of electron exchange potential in quantum plasma. Also, the effect of electron exchange potential on the emission of surface Plasmon's in semiconfined quantum plasma has been investigated [6, 26]. Among the important challenges of this study, we can point out that: Despite investigating the effect of quantum exchange potential on the propagation characteristics of electrostatic waves in quantum plasma [2], this effect on the propagation of magneto-acoustic waves in the quantum semiconductor plasma has not been investigated so far. For this reason, in this article, we intend to study this effect and for this purpose, we use the quantum hydrodynamic2 model (self-consistent Hartree equations or Wigner-Poisson equations) which includes an additional term due to the exchange interaction potential [15, 19].

One class of fundamental plasma waves is low-frequency oscillations in the presence of a magnetic field. These fluctuations include waves such as magneto acoustic and Alfven and create a section called magneto hydrodynamic region in the diagram of plasma waves [17, 24, 29]. The existence of these waves has been proven in various plasma environments and researched under different physical regimes. The dispersion relations related to these waves show well the coupling between acoustic and compression waves (caused by the conduction related to the electric field). The existence of these waves has been proven in various plasma environments and has been studied under different physical regimes [4, 31]. In the research conducted so far in studying the said waves, the plasma environment and its constituent parts are mostly considered classical or relativistic [3, 10, 13, 18]. On the other hand, it has been more than a decade that considering the quantum aspects of the components that make up the plasma has revealed the emergence of new characteristics for some plasma and wave environments and the instabilities in them [9, 14]. Taniuti and Washimi investigated the instability of nonlinear hydro magnetic waves in cold plasma based on a nonlinear dispersion equation [30]. Mushtaq et.al using the QMHD model, Qamar studied the magnetic waves in the electron-ion Fermi plasma. In the linear approximation, the effect of quantum corrections for fast and slow magnetic waves is discussed and it is found that the results obtained for quantum plasmas are significantly different from classical e-i plasmas [25]. Hussain et al studied nonlinear magneto-acoustic waves in a homogeneous and non-collision magnetic quantum plasma and in his research investigated the effects of plasma density and magnetic field intensity on individual magneto acoustic structures in quantum plasma [16]. Bhakta et al after investigating small-amplitude quantum magneto hydrodynamic waves and linear instabilities in dense quantum plasma, analyzed fast, slow, and medium QMHD wave modes [5].

The researches that have been done so far about these waves have mostly been done in classical or relativistic regimes. Some cases have been studied to study linear waves in quantum plasma using the quantum magneto hydrodynamics model, taking into account the quantum Boehm potential without investigating the effect of the exchangecorrelation of plasma particles. Investigations show that previous studies lack a case in which the effects of exchange-correlation and quantum aspects of all plasma components have been studied at the same time, and the most important novelty of the present work can be considered the addition of these relationships together. Therefore first, taking into consideration the quantum aspects of a hot and magnetic plasma environment, the set of equations governing the environment is investigated. Then, while obtaining a kind of generalized scattering relation, the propagation of magnetoacoustic waves is studied. In the end, after making numerical estimates and examining special cases, the conclusion of the research is presented. Considering the limit states, the results of the present work are exactly similar to the results of other researchers, and this can be a self-confirmation of the obtained results. On the other hand, the results obtained for the investigation of nonlinear waves in semiconductor plasma can be strategic and efficient for researchers in the field of Nonlinear Dynamical Systems.

2 Assumptions and analytical calculations

It is assumed that the plasma environment consists of electrons and holes and the governing equations of the environment are affected by the forces related to thermal, quantum, and electromagnetic aspects. In addition, it is assumed that the plasma environment is under the influence of the external magnetic field B_0 (aligned with the zaxis) [11]. In order to analyze the electrodynamic behavior of the considered environment and waves, we recall the first equations below:

$$\nabla \times E = -\frac{\partial B}{\partial t}, \quad \text{and} \quad \nabla \cdot E = 4\Pi\Sigma_{\alpha=e,h} q_\alpha (n_{ho} - n_{e0}) \tag{2.1}$$

$$\nabla \times B = \epsilon_0 \mu_0 \frac{\partial E}{\partial t} - 4\Pi\Sigma_{\alpha=e,h} q_\alpha (n_{ho} V_{hx} - n_{e0} V_{ex}), \quad \text{and} \quad \nabla \cdot B = 0. \tag{2.2}$$

Using the spatial derivative of Maxwell's third equation (Faraday's Law) and the time derivative of Maxwell's fourth equation (generalized Ampere's Law) we have:

$$\nabla \times \nabla \times E = \nabla \times (-\frac{\partial B}{\partial t}) \Rightarrow \nabla(\nabla \cdot E) - \nabla^2 E = \nabla \times (-\frac{\partial B}{\partial t}) \tag{2.3}$$

$$\nabla \times (-\frac{\partial B}{\partial t}) = \epsilon_0 \mu_0 \frac{\partial^2 E}{\partial t^2} - \frac{\partial}{\partial t}(4\Pi \Sigma_{\alpha=e,h} q_\alpha (n_{ho} V_{hx} - n_{e0} V_{ex})\ ) \tag{2.4}$$

Considering the Fourier transform for time and space operators (first-order disturbance coefficients corresponding to $\exp i(ky - \omega t\ )$, then $\frac{\partial}{\partial t} = -i\omega$, and $\nabla = ik$), combining the above two equations, the following relationship is obtained:

$$\overrightarrow{k}(\overrightarrow{k} \cdot \overrightarrow{E}) + k^2 \overrightarrow{E} = \frac{i\omega}{\epsilon_0 c^2}(4\Pi \Sigma_{\alpha=e,h} q_\alpha (n_{ho} V_{hx} - n_{e0} V_{ex})\ ) + \frac{\omega^2}{c^2}\overrightarrow{E}. \tag{2.5}$$

Assuming that the electromagnetic waves are transverse and assuming that the oscillating electric field effective on the charge carriers of the environment are along the x-axis, the relationship will be as follows:

$$\epsilon_0(\omega^2 - c^2 k^2) E_x = -i\omega \Sigma_{\alpha=e,h} q_\alpha (n_{ho} V_{hx} - n_{e0} V_{ex}). \tag{2.6}$$

In the next calculations, we will use the modified Euler equation to place the velocity components of holes and electrons. We assume that in the said equation, the forces affecting the movement are Lorentz forces, classical pressure gradient, Boehm's quantum, and the exchange-correlation potential:

$$m_\alpha n_{i\alpha} \frac{\partial V_{i\alpha}}{\partial t} = q_\alpha n_{i\alpha}(E + V_{i\alpha} \times B_0) - \frac{1}{3} V_{Fi\alpha}^2 m_\alpha \nabla n_{i\alpha} - \frac{\hbar^2}{4m_\alpha}\nabla[\frac{1}{\sqrt{n_{i\alpha}}}\nabla^2 \sqrt{n_{i\alpha}}] - 2^{\frac{4}{3}} q_\alpha^2 \sqrt[3]{\frac{3}{\pi}}\sqrt[3]{n_{i\alpha}}\nabla n_{i\alpha}. \tag{2.7}$$

This equation is the equation of motion of semiconductor plasma components (electrons and holes), where the index α refers to electrons (e) or holes (h), [22]. q_α, m_α, and $n_{i\alpha}$ are the charge, mass, and equilibrium density of the αth plasma component, respectively. The first term on the right side of equation (2.7) refers to the Lorentz force due to the electrostatic potential plus the effect of the external magnetic field. The second term is the force due to the Fermi pressure, where it is assumed that the semiconductor plasma components obey the Fermi state equation. Therefore, the term related to the Fermi pressure is defined as $P_\alpha = (\frac{m_\alpha V_{Fi\alpha}^2}{3n_{i0}^2}) n_{i\alpha}^3$, where $V_{Fi\alpha}^2 = \frac{2K_B T_{F\alpha}}{m_\alpha}$ is the Fermi velocity of the αth component of the plasma. The third term describes the phenomenon of quantum tunneling through the Bohm potential such that $V_{q\alpha} = -(\frac{\hbar^2}{2m_\alpha})\frac{\nabla^2\sqrt{n_{i\alpha}}}{\sqrt{n_{i\alpha}}}$, and $\mu_\alpha = \frac{e\hbar}{2m_\alpha}$ represents the Bohr magneton. The last sentence also refers to the quantum potential exchange-correlation [12].

It is assumed that the plasma is anisotropic and exposed to the external magnetic field B_0. Also, assuming that the range of fluctuations is small, we can analyze the system by linearizing the equations governing the environment. To analyze the dispersion of the system, we use first-order disturbance coefficients corresponding to $\exp i(ky - \omega t\ )$. Therefore, with the Fourier transform, the disturbed magnetic field is obtained from relation (2.1) as $B = -(\frac{kE}{\omega})\widehat{z}$. According to the continuity equation, the disorder densities of plasma particles take the following form:

$$\frac{\partial n_{i\alpha}}{\partial t} + n_{0\alpha}\nabla \cdot V_{i\alpha} = 0 \Rightarrow n_{i\alpha} = \frac{n_{o\alpha k}}{\omega}\widehat{y} \cdot V_{1\alpha}. \tag{2.8}$$

By applying the Fourier transform to Euler's Eq. (2.7), we will have:

$$-i\omega m_\alpha n_{0\alpha} V_{1\alpha} = q_\alpha n_{0\alpha}(E_x + V_{1\alpha} \times B_0) - \frac{i}{3} V_{Fi\alpha}^2 m_\alpha n_{1\alpha} k\widehat{y} - \frac{i\hbar^2}{4m_\alpha} k^3 n_{1\alpha}\widehat{y} - i2^{\frac{4}{3}} q_\alpha^2 \sqrt[3]{\frac{3}{\pi}} n_{1\alpha}^{\frac{4}{3}}\widehat{y}. \tag{2.9}$$

From the combination of relations (2.8) and (2.9) with a few mathematical operations, we will have:

$$-i\omega V_{1\alpha} = \frac{q_\alpha}{m_\alpha}(E_x + V_{1\alpha} \times B_0) + \psi_\alpha (k \cdot V_{1\alpha}) k. \tag{2.10}$$

In the last relation, the quantity $\psi_\alpha = -\frac{i}{\omega}[\frac{\hbar^2 k^2}{4m_\alpha} + \frac{\gamma_\alpha K_B T_{F\alpha}}{m_\alpha} + \frac{2^{\frac{4}{3}} q_\alpha^2}{m_\alpha}\sqrt[3]{\frac{3n_{1\alpha}}{\pi}}]$ is defined, and in the following, the required speed components of the particles are obtained from relation (2.10) for electrons and holes as follows:

$$\begin{cases} V_{\alpha x} = \frac{iq_\alpha}{m_\alpha \omega}(E_x + V_{\alpha y} \times B_0) \\ V_{\alpha y} = \frac{iq_\alpha}{m_\alpha \omega}(-V_{\alpha x B_0}) + \frac{k^2}{\omega^2}[\frac{\hbar^2 k^2}{4m_\alpha^2} + \frac{\gamma_\alpha K_B T_{F\alpha}}{m_\alpha} + \frac{2^{\frac{4}{3}} q_\alpha^2}{m_\alpha}\sqrt[3]{\frac{3n_{1\alpha}}{\pi}}] v_{\alpha y} \end{cases} \Rightarrow V_{\alpha y} = \mp \frac{i\omega_{c\alpha}}{\omega(1 - \tau_\alpha)} V_{\alpha x}. \tag{2.11}$$

From the combination of the above relationships, $V_{\alpha x}$ is obtained as follows:

$$V_{\alpha x} = \pm \frac{iq_\alpha}{m_\alpha \omega} E_x \left(\frac{1-\tau_\alpha}{1-\tau_\alpha - \frac{\omega_{c\alpha}^2}{\omega^2}} \right), \omega_{c\alpha} = \frac{q_\alpha^2 B_0^2}{m_\alpha^2} \tag{2.12}$$

where

$$\tau_\alpha = \frac{k^2}{\omega^2} \left[\frac{\hbar^2 k^2}{4m_\alpha^2} + \frac{\gamma_\alpha K_B T_{F\alpha}}{m_\alpha} + \frac{2^{\frac{4}{3}} q_\alpha^2}{m_\alpha} \sqrt[3]{\frac{3n_{1\alpha}}{\pi}} \right]. \tag{2.13}$$

With the assumption of $\omega \ll \omega_{c\alpha}$ and the definition of cyclotron frequency, the relation (2.12) can be written as follows:

$$V_{\alpha x} = \pm \frac{iq_\alpha}{m_\alpha \omega} E_x \frac{\omega^2}{\omega_{c\alpha}^2} (1-\tau_\alpha). \tag{2.14}$$

By placing the obtained velocities (2.14) for electrons and holes in the relation (2.6), the general dispersion relation is obtained as follows:

$$\omega^2 - c^2 k^2 = \frac{iq_\alpha n_{0\alpha} \omega}{\epsilon_0} \left[\frac{iq_\alpha}{m_\alpha \omega} \left(\frac{1-\tau_\alpha}{1-\tau_\alpha - \frac{\omega_{c\alpha}^2}{\omega^2}} \right) + \frac{ik^2}{\omega B_0^2} \left(\frac{\gamma_\alpha K_B T_{F\alpha}}{m_\alpha q_\alpha} + \frac{2^{\frac{4}{3}} q_\alpha^3}{m_\alpha} \sqrt[3]{\frac{3n_{1\alpha}}{\pi}} \right) + \frac{i\hbar^2 k^4}{4m_\alpha^2 \omega q_\alpha B_0^2} \right]. \tag{2.15}$$

The obtained equation, according to the definition of Alfven speed $V_{A\alpha}^2 = \Sigma_{\alpha=e,h} \frac{B_0^2}{m_\alpha n_{0\alpha}}$ and plasma frequency $\omega_{p\alpha}^2 = \frac{n_{0\alpha} q_\alpha^2}{\epsilon_0 m_\alpha}$ and with a little mathematical operation, is converted as follows:

$$\omega_{p\alpha}^2 (1-\tau_\alpha) = \left[\omega^2 - c^2 k^2 \left(1 + \frac{\frac{\hbar^2 k^2}{4m_\alpha^2} + \frac{\gamma_\alpha K_B T_{F\alpha}}{m_\alpha} + \frac{2^{\frac{4}{3}} q_\alpha^2}{m_\alpha} \sqrt[3]{\frac{3n_{1\alpha}}{\pi}}}{V_{A\alpha}^2} \right) \right] \left[(1-\tau_\alpha) - \frac{\omega_{c\alpha}^2}{\omega^2} \right]. \tag{2.16}$$

In the next step, by inserting the representative expression τ_α in relation (2.16), it is obtained:

$$\omega^4 - \omega^2 (\omega_{c\alpha}^2 + c^2 k^2 \omega_{p\alpha}^2 + \delta c^2 k^2 + \epsilon) + \delta c^2 k^2 \omega_{c\alpha}^2 + \epsilon (\delta c^2 k^2 + \omega_{p\alpha}^2) = 0. \tag{2.17}$$

In order to shorten the above relationship, the following parameters are defined:

$$\delta = 1 + \left(\frac{\frac{\hbar^2 k^2}{4m_\alpha^2} + \frac{\gamma_\alpha K_B T_{F\alpha}}{m_\alpha} + \frac{2^{\frac{4}{3}} q_\alpha^2}{m_\alpha} \sqrt[3]{\frac{3n_{1\alpha}}{\pi}}}{V_{A\alpha}^2} \right), and \epsilon = k^2 \left(\frac{\hbar^2 k^2}{4m_\alpha^2} + \frac{\gamma_\alpha K_B T_{F\alpha}}{m_\alpha} + \frac{2^{\frac{4}{3}} q_\alpha^2}{m_\alpha} \sqrt[3]{\frac{3n_{1\alpha}}{\pi}} \right). \tag{2.18}$$

Considering the complexity of the obtained expression, we use a suitable approximation for simplification, for this purpose we ignore the expression $(1-\tau_\alpha)$ compared to $\frac{\omega_{c\alpha}^2}{\omega^2}$.

$$\left[\omega^2 - c^2 k^2 \left(1 + \frac{\frac{\hbar^2 k^2}{4m_\alpha^2} + \frac{\gamma_\alpha K_B T_{F\alpha}}{m_\alpha} + \frac{2^{\frac{4}{3}} q_\alpha^2}{m_\alpha} \sqrt[3]{\frac{3n_{1\alpha}}{\pi}}}{V_{A\alpha}^2} \right) \right] = -\frac{\omega_{p\alpha}^2}{\omega_{c\alpha}^2} \left[\omega^2 - k^2 \left(\frac{\hbar^2 k^2}{4m_\alpha^2} + \frac{\gamma_\alpha K_B T_{F\alpha}}{m_\alpha} + \frac{2^{\frac{4}{3}} q_\alpha^2}{m_\alpha} \sqrt[3]{\frac{3n_{1\alpha}}{\pi}} \right) \right]. \tag{2.19}$$

To present a better form Eq. (2.19), we use the definition of acoustic velocity $V_{s\alpha}^2 = \Sigma_{\alpha=e,h} \frac{\gamma_\alpha K_B T_{F\alpha}}{m_\alpha}$, and $\frac{\omega_{p\alpha}^2}{\omega_{c\alpha}^2} = \frac{c^2}{V_{A\alpha}^2}$, finally the relationship is rewritten as follows:

$$\omega^2 (c^2 + V_{A\alpha}^2) = c^2 k^2 \left(V_{s\alpha}^2 + V_{A\alpha}^2 + \frac{\hbar^2 k^2}{4m_\alpha^2} + \frac{2^{\frac{4}{3}} q_\alpha^2}{m_\alpha} \sqrt[3]{\frac{3n_{1\alpha}}{\pi}} \right). \tag{2.20}$$

The obtained expression expresses the sputtering relationship in plasma, which is obtained in a general state by considering quantum, thermal, and magnetic field effects. The last two attacks on the right side of the equation show well the effect caused by the quantum Boehm potential and the exchange-correlation potential on the scattering of waves in the plasma medium. In addition, in the next section, it will be shown that the special cases of this equation will lead to what results.

3 Discussion and review

In this section, in order to have a better understanding of the obtained results, we examine the special cases in equation (2.20).

1. Cold quantum and magnetic plasma state

In this case and in the absence of temperature effects, i.e. $\Sigma_{\alpha=e,h}T_{F\alpha} \to 0$, equation 20 becomes as follows:

$$\omega^2(c^2+V_{A\alpha}^2)=c^2k^2(V_{A\alpha}^2+\frac{\hbar^2k^2}{4m_\alpha^2}+\frac{2^{\frac{4}{3}}q_\alpha^2}{m_\alpha}\sqrt[3]{\frac{3n_{1\alpha}}{\pi}}). \tag{3.1}$$

This relationship can be called the modified Alfven wave representative and is affected by quantum effects.

2. Classical plasma

In the absence of quantum effects ($\hbar \to 0$), equation (2.20) is rewritten as follows:

$$\omega^2(c^2+V_{A\alpha}^2)=c^2k^2(V_{s\alpha}^2+V_{A\alpha}^2+\frac{2^{\frac{4}{3}}q_\alpha^2}{m_\alpha}\sqrt[3]{\frac{3n_{1\alpha}}{\pi}}). \tag{3.2}$$

As we know, this relationship is related to a non-scattering magneto-acoustic wave in which $\frac{2^{\frac{4}{3}}q_\alpha^2}{m_\alpha}\sqrt[3]{\frac{3n_{1\alpha}}{\pi}}$ is collected, this wave is propagated perpendicular to the magnetic field in the classical environment [20, 23]. As can be seen from the relationship, the phase speed of this magnetosonic mode is greater than the Alfven speed, which is why it is usually called a fast hydromagnetic wave.

3. Classical plasma state in the absence of magnetic field

In the absence of quantum and magnetic effects ($\hbar \to 0$, and $B_0 \to 0$), equation (2.20) becomes as follows:

$$\omega^2=k^2(V_{s\alpha}^2+\frac{2^{\frac{4}{3}}q_\alpha^2}{m_\alpha}\sqrt[3]{\frac{3n_{1\alpha}}{\pi}}). \tag{3.3}$$

This relationship is the scattering relationship of the acoustic wave, in which case the magnetoacoustic wave becomes a normal acoustic wave. From the results and discussion presented so far, the effects of considering thermal, quantum and magnetic field aspects on the scattering relationship and especially the effect of quantum considerations on the scattering of waves are obvious.

4 Conclusion

In this article, the propagation of magneto acoustic waves in a semiconductor quantum plasma environment was investigated. For this purpose, a set of quantum fluid equations, including Maxwell's equations, fluid equations of motion, and continuity, were used to obtain a generalized dispersion relation for the desired waves. The relations obtained (Eq. (2.20)) show a more complex form than the classical state and include effects arising from the application of quantum forces. Due to the complexity of the relationship obtained, the special modes of wave propagation were discussed separately and compared with the classical mode. Previous results in this field are also retrieved. In semiconductor quantum plasma, scattering effects are due to charge separation between electrons and holes, quantum repulsion, nonlinearities due to large amplitude electrostatic potential, quantum degeneracy pressure, and correlation 7 exchange interaction. Also, according to the result related to the scattering of waves, it is also affected by the quantum aspects of plasma. On the contrary, the examination of more specific modes showed that they have the same scattering state in the waves as the classical mode. In addition, the external magnetic field also increases the frequency of magneto-acoustic waves in the quantum semiconductor plasma under investigation. Consciously, the examination of the limit states showed that the resulting generalized relation in special states will represent the modified quantum Alfven wave, the modified classical Alfven wave, and the ordinary acoustic wave, respectively. Propagation under different angles of the magneto-acoustic waves with respect to the external magnetic field can be a problem of interest, but is beyond the scope of the present research and is left for future work. The present results may be useful for understanding the scattering properties of magneto-acoustic wave oscillations that may be propagated at the plasmavacuum interface in electron-hole semiconductor plasmas or in solid density plasma with a numerical density of $n_{j0}=10^26m^3$ and a magnetic field strength $B_0=1-2T$ [1, 7].

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