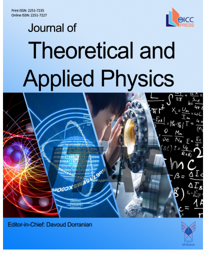

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Scattering of quantum hydromagnetic waves in a semiconductor plasma

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Abstract:
In addition to the fact that waves have been proven in different plasma environments, they have also been investigated under different physical regimes. In this research, the propagation of electromagnetic waves in quantum semiconductor plasma in the presence of a uniform external magnetic field was investigated using the quantum hydro magnetism model. 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, taking into account the quantum Bohm potential without investigating the effect of the spin characteristics of plasma particles. In addition to the simultaneous study of spin and quantum effects of semiconductor plasma components, exchange-correlation relationships have not been found in any research, and the most important novelty of the present work can be considered the addition of these relationships together. The obtained results show that the effects of quantum and external magnetic fields have a significant effect on the scattering of hydromagnetic waves, which causes the appearance of nonlinear terms in the scattering relationship. By increasing the linear part of the electron spin in the sputtering relation, some relations have been modified, including the Alfven velocity. On the other hand, the effect of electron spin leads to the reduction of the effect of other quantum potentials on the scattering of waves. In the end, some special states of classical and quantum systems are also discussed. 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.

Keywords: Hydromagnetic waves; Dispersion relation; QHD model; Quantum plasma; Semiconductor plasma

1. Introduction

Plasma is a collection of charged particles, which is regarded as a multi-particle system from a statistical point of view. Charged plasma particles can interact with each other due to the electrostatic potential with a range longer than the average distance between particles, so the correlation between plasma particles cannot be ignored [1–3]. Charge carriers in semiconductors form a plasma that exhibits collective self-behavior like gas plasmas. In the last three decades, much research has been conducted concerning the excitation of linear and nonlinear waves and their instabilities in solid-state plasmas. In physical environments, quantum effects become effective if plasma particles' wavelength is comparable to the plasma's spatial scale [4]. In general, in environments where the density of carriers is relatively high and the temperature is low, the presence of quantum phenomena in the dynamic behavior of plasma is inevitable [5–7]. In addition, in semiconductor plasmas, the wavelength of the charge carriers is comparable to the longitudinal characteristics of the system, such as the interparticle distance or Winger radius, and the environment can be considered quantum [8]. On the other hand, most of the recent studies with quantum models show significant changes in the linear and nonlinear electrodynamic properties of semiconductor systems compared to the classical model [9].

In previous research and many other similar works, most of the classical aspects of plasma particles have been considered and quantum effects have not been considered. On the other hand, in recent years, the influence of the quantum aspects of particles on the behavior of plasma environments has been noticed and has taken a considerable part of the studies [10, 11]. In many cases, considering the quantum aspects of plasma particles changes the relations and results of various analytical calculations compared to the classical state [12]. After analytical calculations, numerical and graphical estimates determine the importance and effect of quantum corrections compared to the numerical results of the classical mode. The reason for paying attention and dealing with these calculations is the possibility of influencing and relating them to developments, and emerging fields in physical systems such as ultra-fine electronic devices, semiconductor devices, quantum dots, carbon nanotubes, microplasmas, dense astrophysical systems, etc. On the other hand, the study of waves and instabilities in quantum plasma to understand collective behaviors in intense laser-plasma interactions; Microelectronic devices, and metallic nanostructures are of fundamental importance [13–15]. In the 1960s, for the first time, discussions about quantum plasma were raised by Pines in physical regimes with high density and low temperature [16–19]. Taniuti and Washimi investigated the instability of nonlinear hydromagnetic waves in cold plasma based on a nonlinear dispersion equation [20]. 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 [21]. 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 [22].

The first researches conducted in the field of quantum semiconductor plasmas go back to 2010, but the research related to understanding the behavior and characteristics of waves in these plasmas is limited. The quantum hydrodynamic model has been widely used to study the diffusion characteristics in quantum plasma systems [23, 24]. In research using the quantum hydrodynamics model, the linear characteristics of the longitudinal electrokinetic wave in a quantum semiconductor plasma were investigated and analyzed. Also, the propagation characteristics of electrokinetic methods in classical and quantum processes have been evaluated. Others have investigated the excitation of helicon waves in a quantum semiconductor plasma for current carriers [25]. 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 arises from the electrostatic potential (Hartree theorem), and the other is known as the electron exchange effect [26]. The electron exchange effect is a complex function of the electron density and is obtained through the local density approximation. Jung et al. investigated the effect of electron exchange potential on the charge-trapping process in degenerate quantum plasma [27]. In fact, the electron-hole (e-h) plasma represents the core to understanding the properties of several types of semiconductor devices, which has also already been used in designing high-power semiconductor devices, such as superluminescent diodes (SLEDs), There are many reports about this such as: Zang et al. investigated the low thermal resistance of high power superluminescence diodes (SLED) using active multimode interferometer (active-MMI) [28]. Zeba et al. studied the electron-hole two-stream instability in a quantum semiconductor plasma and showed that considering the phonon susceptibility allows for the acoustic mode to exist, and the collisional instability arises in combination with hole drift [29]. Yahia et al. investigated wave propagation in GaAs semiconductor and showed that the propagation modes are unstable and strongly depend on electron beam parameters as well as quantum recoil effects and depletion pressures [30].

In the discussion of plasma waves, hydromagnetic waves are one of the most important categories. The existence of these waves has been proven in different plasma environments and has been investigated under different physical regimes. The research that has been done so far on these waves has mostly been done in classical or relativistic regimes. In many cases, a part of the quantum plasma components and a classical part have been considered, or the characteristic effect of the spin of plasma particles has been neglected. Investigations show that previous studies on semiconductor plasma lack a case where the effects of electron spin and Quantum forces due to fluctuations in the density of electrons and holes should be considered simultaneously. Therefore, in the present work, by using the modified quantum hydromagnetic equations, first by considering the spin of electrons and also by considering the quantum potential of electrons and holes forming the plasma, the propagation of these waves in semi-conducting plasma, including hole-electrons isothermal has been studied. Electrons are assumed to obey Fermi-Dirac statistics with magnetic spin energy and other quantum effects such as Bohm's quantum potential. The holes are also assumed to be quantum and the quantum Bohm potential is considered for them. It has been tried to obtain a more general relationship for spraying under the influence of all mentioned quantum effects by using the generalized equations of quantum fluid and to discuss and investigate the propagation of hydromagnetic waves in different states of the environment with an external magnetic field. And in the final part, numerical analysis is done. And the result of the research will be presented.

2. Basic equations

Using the equations of motion for the network and the equations of the quantum hydrodynamic model (QHD) for plasma, the wave scattering relation is obtained. The Schrodinger-Poisson model describes the hydrodynamic behavior of plasma components on a quantum scale. The study of quantum kinetic behavior in plasma is also possible with the Wigner-Poisson model. The QHD model is obtained by considering the velocity torques in the Wigner relations [31]. In fact, the QHD model is the equivalent of the classical fluid for plasma, which is more complete with the quantum correction term (such as the Bohm potential). In this model, the quantum statistical effect is also considered through the equations of state. The set of equations that describe the dynamic behavior of electrons and holes in magnetic quantum semiconductor plasma are [12]:

$$\frac{\partial n_{\alpha j}}{\partial t} + n_{j0}\nabla \cdot \mathbf{V}_{\alpha j} = 0 \tag{1}$$

where the index j refers to electrons (e) or holes (h). Another important equation is the modified Euler equation for plasma particles and is written as follows:

$$m_j^* n_{\alpha j}\frac{d\mathbf{V}_{\alpha j}}{dt} = \mathbf{F}_L + \mathbf{F}_P + \mathbf{F}_Q + \mathbf{F}_S + \mathbf{F}_E \tag{2}$$

This equation is the equation of motion of semiconductor plasma components (electrons and holes) [1]. q_j, m_j^* and $n_{\alpha j}$ are the charge, effective mass and equilibrium density of the jth plasma component, respectively. The first term on the right side of Equation 2 refers to the Lorentz force due to the electrostatic potential plus the effect of the external magnetic field $(-q_j\nabla\varphi + q_j\mathbf{V}_{\alpha j}\times\mathbf{B}_0)$. 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 $P_j = (m_j^* V_{Fj}^2/3n_{j0}^2)n_{\alpha j}^3$, where $V_{Fj}^2 = 2K_BT_{Fj}/m_j^*$ is the Fermi velocity of the jth component of the plasma. The third term describes the phenomenon of quantum tunneling through the Bohm potential such that $V_{qj} = -(k^2/2m_j^*)\nabla^2\sqrt{n_{\alpha j}}/\sqrt{n_{\alpha j}}$. The fourth term of the spin magnetization force is caused by the spin interaction with the external magnetic field, which is very important in highly magnetic and dense environments. On the other hand, the quantum term caused by density fluctuations is important in all dense and semi-dense quantum plasmas (semiconductors), magnetic and non-magnetic environments, cold and hot plasmas. Also, in this regard, electron spin is considered a constant physical quantity and is not a dynamic variable. Therefore, spin plays the role of the spin magnetization force in the equation of motion (it is used from all nonlinear terms of spin) and $\mu_j = e\hbar/2m_j^*$ represents the Bohr magneton. The last sentence also refers to the quantum exchange correlation. In relation $dV/dt = \partial V/\partial t + (V\cdot\nabla)V$, where $\partial V/\partial t$ is change of velocity with time and $(V\cdot\nabla)V$ is convective time. In this research, the velocities of both types of particles in the equilibrium state were considered zero ($V_{e0} = V_{h0} = 0$), and we consider the equilibrium density as $n_{e0} = n_{h0} = n_0$. In order to linearize the sentences in the above relationship, we consider the quantity ξ, which represents each of the physical quantities (**B**, **E**, $\mathbf{V}_\alpha$, and n_α). The above quantity includes an equilibrium part (ξ_0) and a very small fluctuating part (ξ_1). Considering the fluctuating part as $\xi_1 = \xi_1 \exp i(ky-\omega t)$, form of Equation 2 and Poisson's equation will be:

$$\begin{aligned} m_j^* n_{\alpha j}\frac{\partial V_{\alpha j}}{\partial t} =& q_j n_{\alpha j}(E + V_{\alpha j}\times B_0) - \frac{1}{3}V_{F\alpha j}^2 m_j^*\nabla n_{\alpha j} - \\ & \frac{\hbar^2}{4m_j^*}\nabla\left[\frac{1}{\sqrt{n_{\alpha j}}}\nabla^2\sqrt{n_{\alpha j}}\right] - \\ & \frac{2\mu_j n_{\alpha j}}{\hbar}\nabla(B_0, S_{\alpha j}) - 2^{\frac{4}{3}}q_j^2\sqrt{\frac{3}{\pi}}\sqrt[3]{n_{\alpha j}}(\nabla n_{\alpha j}) \end{aligned} \tag{3}$$

$$\nabla^2\varphi = 4\pi e(n_h - n_e) \tag{4}$$

The velocities of each species of particles in the equilibrium state are considered zero ($V_{j0} = 0$). In addition to continuity and motion equations, to describe electromagnetic waves, we mention Maxwell's equations as follows:

$$\begin{aligned} \nabla\times E_1 =& -\frac{\partial B_1}{\partial t}, \\ \nabla\cdot E_1 =& 4\pi e(n_h - n_e) \end{aligned} \tag{5}$$

$$\begin{aligned} \nabla\times B_1 =& \mu_0\varepsilon_0\frac{\partial E_1}{\partial t} - 4\pi e(n_{e0}V_e - n_{h0}V_h) + J_{Mj}, \\ \nabla\cdot B_1 =& 0 \end{aligned} \tag{6}$$

The last term of this relationship contains the total current density $J_{Mj} = -\nabla\times(2n_j\mu_jS/h)$, where the spin magnetization current density results from the spin interaction with the external magnetic field and S is the spin vector.

3. Numerical analysis

In order to study the propagation characteristics of waves that can propagate at the boundary between a semiconducting quantum plasma piece and under the influence of quantum forces such as the force caused by the Boehm potential and the exchange interaction potential, we consider semiconducting quantum plasma consisting of electrons and holes, which is limited between planes $X = 0$ and $X = L$ according to the Figure 1, and is exposed to an external and uniform magnetic field B_0 applied in a direction parallel to this boundary surface.

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 Equation 5 as $B_1 = -(kE_1/\omega)\hat{z}$. According to the continuity equation, the disorder density of plasma particles takes the following form:

$$n_{\alpha j} = \frac{n_{j0}k}{\omega}\hat{y}\cdot V_{j1} \tag{7}$$

In the continuation of the calculations, by substituting the velocity components of the plasma particles from the modified Euler equations as well as the magnetizing current density, we obtain a kind of general sputtering relation. Therefore, in the next step, we determine the spin equilibrium shape. Therefore, when the external magnetic field is considered

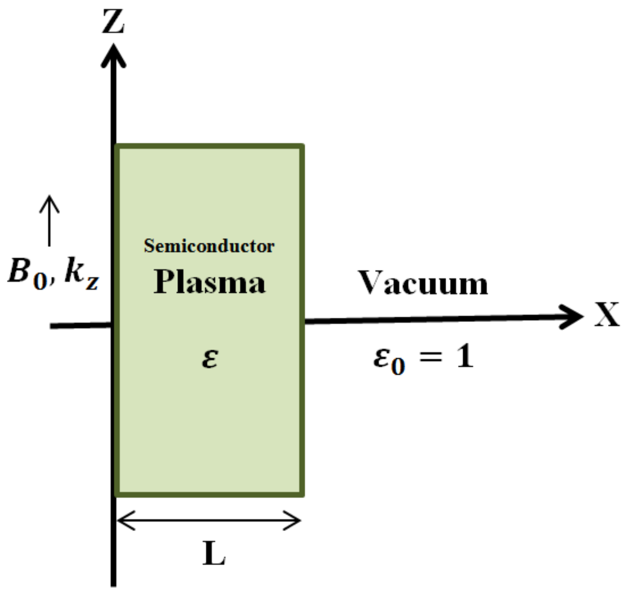

Figure 1. Geometrical structure of semiconductor plasma.

as $(B_0 = B_{0y}, B_{0z})$, the zeroth order of magnetization (M_{S0}) caused by spin is written as follows [12].

$$M_{S0} = n_0\mu_B\eta\left(\frac{\mu_B B_0}{K_B T_{Fe}}\right)\hat{B} \tag{8}$$

In which, for simplicity, the Brillouin function due to the magnetization of a spin distribution in thermodynamic equilibrium is introduced as $\eta(\alpha) = \tanh(\alpha)$. Here $\alpha = (\mu_B B_0/K_B T_{Fe})$, and $T_{Fe} = (3\pi^2 n_e)^{(2/3)}\hbar^2/(2K_B m_e)$ is the Fermi temperature of electrons in the temperature of the plasma. In general, spin magnetization M_S and spin vector S are related as follows:

$$S = \frac{\hbar M_S}{2n_e\mu_B} \tag{9}$$

In this case, the zeroth order of the spin vector is obtained from the combination of Eqs. 9 and 10 in the form of $S_0 = -(\hbar/2)\eta(\alpha)(\cos\theta\hat{y} + \sin\theta\hat{z})$. By replacing S_0 and n_{j1}, the spin magnetization current is obtained $J_{Mj} = (i\mu_j\eta(\alpha)n_{j0}k^2 V_{\alpha j}\sin\theta\hat{x})/\omega$. On the other hand, by applying the Fourier transform to Euler's equation, we will have 3:

$$\begin{aligned}-i\omega m_j^* n_{j0}V_{j1} = &q_j n_{j0}(E + V_{j1}\times B_0) - \frac{i}{3}V_{F\alpha j}^2 m_j^* n_{j1}k\hat{y} - \\ &\frac{i\hbar^2}{4m_j^*}k^3 n_{j1}\hat{y} + i\eta(\alpha)n_{j0}B_1 k\sin\theta\hat{y} - \\ &i2^{\frac{4}{3}}q_j^2\sqrt{\frac{3}{\pi}}n_{j1}^{\frac{4}{3}}\hat{y}\end{aligned} \tag{10}$$

In the following, the required speed components of the particles are obtained from the Equation 10 for electrons and holes as follows:

$$\begin{aligned}V_{1jx} = &\left(\frac{\omega^2(1-\beta_j)}{\omega^2(1-\beta_j) - \omega_{cj}^2 + \omega_{cj}^2\cos^2\theta\beta_j}\right) \\ &\left[\left(\frac{-ie}{\omega m_j^*}E_x\right) - \left(\frac{i\omega_{cj}\eta(\alpha)k^2\mu_j\sin^2\theta}{m_j^*\omega(1-\beta_j)\omega^2}E_x\right)\right]\end{aligned} \tag{11}$$

and

$$\begin{aligned}V_{1yj} = &\frac{\eta(\alpha)k^2\mu_j\sin\theta}{m_j^*(1-\beta_j)\omega^2}E_x + \\ &\left[\frac{i\omega_{cj}\sin\theta}{\omega(1-\beta_j)}\left(\frac{-ie}{\omega m_j^*}E_x\right) - \left(\frac{i\omega_{cj}\eta(\alpha)k^2\mu_j\sin^2\theta}{m_j^*\omega(1-\beta_j)\omega^2}E_x\right)\right] \\ &\left[\frac{\omega^2(1-\beta_j)}{\omega^2(1-\beta_j) - \omega_{cj}^2 + \omega_{cj}^2\cos^2\theta\beta_j}\right]\end{aligned} \tag{12}$$

In these relationships, the following definition is used for simplification:

$$\begin{aligned}\beta_j = &\left(\frac{V_{Fj}^2}{3} + \frac{\hbar^2 k^2}{4m_j^2} - 2^{\frac{4}{3}}\sqrt[3]{\frac{3}{\pi}}\frac{q_j^2}{m_j^*}n_{j0}^{\frac{1}{3}}\right), \\ \omega_{cj} = &\frac{q_j B_0}{m_j^*}, \text{ and} \\ \omega_{pj} = &\sqrt{\frac{q_j^2 n_{j0}}{\varepsilon_0 m_j^*}}\end{aligned} \tag{13}$$

By placing the obtained velocities 11 and 12 in the Equation 8, the general sprinkling relation is obtained as follows:

$$\begin{aligned}\omega^2 - c^2k^2 = &\omega_{pj}^2\left[1 + \frac{2\omega_{cj}\eta(\alpha)\mu_j k^2\sin^2\theta}{q_j(1-\beta_j)\omega^2} + \right. \\ &\left.\frac{\eta^2(\alpha)\mu_j^2 k^4\sin^2\theta}{q_j^2(1-\beta_j)\omega^2}\left(1 - \frac{\omega_{cj}^2}{\omega^2}\cos^2\theta\right)\right]\times \\ &\left[\frac{\omega^2(1-\beta_j)}{\omega^2(1-\beta_j) - \omega_{cj}^2 + \omega_{cj}^2\cos^2\theta\beta_j}\right]\end{aligned} \tag{14}$$

This relation shows the scattering of hydromagnetic waves in degenerate semiconductor plasma and in the presence of quantum effects caused by the quantum Bohm potential, the electron spin effect, and the exchange correlation. In the next section, it will be shown that the special states of this equation will include known relationships and results.
To check the effect of dielectric in sputtering relationships, it is enough to enter ε in Equation 15:

$$\begin{aligned}k = &\frac{\omega}{c}\left[\varepsilon - \omega_{pj}^2 - \frac{2\omega_{pj}^2\omega_{cj}\eta(\alpha)\mu_j k^2\sin^2\theta}{q_j(1-\beta_j)\omega^2} + \right. \\ &\left.\frac{\omega_{pj}^2\eta^2(\alpha)\mu_j^2 k^4\sin^2\theta}{q_j^2(1-\beta_j)\omega^2}\left(1 - \frac{\omega_{cj}^2}{\omega^2}\cos^2\theta\right)\right]^{\frac{1}{2}}\times \\ &\left[\frac{\omega_{pj}^2\omega^2(1-\beta_j)}{\omega^2(1-\beta_j) - \omega_{cj}^2 + \omega_{cj}^2\cos^2\theta\beta_j}\right]^{\frac{1}{2}}\end{aligned} \tag{15}$$

in this relation, ε is the dielectric constant of the system.

4. Discussion and review

Equation 15 has a relatively complex form and the influence of various factors is obvious in it. In the following, its different modes will be examined.
a) Spin electron-hole plasma

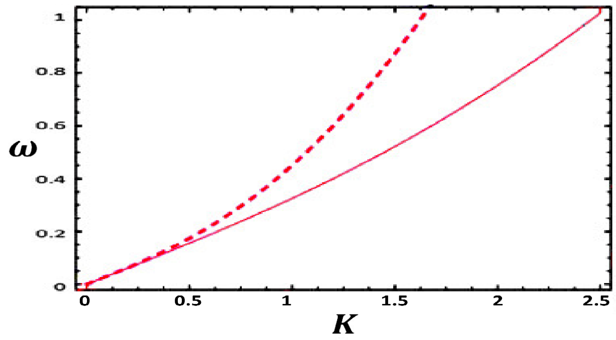

Figure 2. The presence (solid line) and absence (dashed line) of the spin magnetization effect in the relation of hydromagnetic wave scattering are shown.

We assume that there are no additional charged particles in the plasma environment, so for perpendicular propagation ($\theta = \pi/2$) Equation 15 is reduced as follows:

$$\omega^2 = \frac{c^2k^2}{V_{jA}^2 + c^2}[V_{jA}^2 + V_{F\alpha j}^2 + \frac{\hbar^2 k^2}{4m_j^2}(2 - \eta^2(\alpha)) - \gamma_j \omega_{pj}^2],$$
$$\gamma_j = \sqrt[3]{\frac{3}{(2\pi^2)^2}}(n_{j0}^{-\frac{2}{3}}) \quad (16)$$

In this equation, $V_{jA}^2 = B_0/\sqrt{\mu_j n_{j0} m_j}$ is the Alfven speed. Equation 16 shows the quantum and modified form of spin for the scattering relationship of semiconductor hydromagnetic waves, the term related to spin appeared in the last sentence on the right side. As it is evident from Equation 16, the quantum effects caused by the drop in the density with a positive sign increase the scattering, so that the effect of spin magnetization shows a decreasing contribution to the scattering of these waves, contrary to the terms of quantum diffraction. Here, c represents the speed of light, and the quantum correction caused by the correlation potential as γ_j e reduces the Alfven speed in equation to 16. For parallel propagation ($\theta = 0$), Equation 15 will be as follows:

$$\omega = V_{iA} k \quad (17)$$

This relation is related to the Alfven wave, which is not affected by quantum effects.

b) **Non-spin electron-hole plasma**

Ignoring the effect of particle spin ($\eta(\alpha) \to 0$) and considering the perpendicular propagation mode ($\theta = \pi/2$), Equation 16 is reduced to the following form:

$$\omega^2 = \frac{c^2k^2}{V_{jA}^2 + c^2}[V_{jA}^2 + V_{F\alpha j}^2 + \frac{\hbar^2 k^2}{2m_j^2} - \gamma_j \omega_{pj}^2] \quad (18)$$

In this case, the quantum correction related to the quantum potential of electrons and holes is seen. It is clear from this relationship that in this case, the Bohm potentials of electrons and holes have an increasing contribution to the wave scattering, although the scattering depending on the holes is less. The speed of the modified spiny Alfven is also converted to the classical Alfven speed V_{jA}. In the case of parallel propagation, we will reach the relation obtained in the previous section (Eq. 17).

c) **Classical plasma**

If we don't consider any of the quantum effects, i.e. in the limit ($k \to 0$) for semiconductor plasma, Eq. 16 reaches the well-known relations for compressive hydromagnetic waves:

$$\omega^2 = c^2k^2\left(\frac{V_{jA}^2 + V_{F\alpha j}^2 - \gamma_j \omega_{pj}^2}{V_{jA}^2 + c^2}\right) \quad (19)$$

This relation shows the classical magneto-acoustic wave scattering relation. In general, quantum effects have had a significant impact on the scattering Eq. 16 compared to its classical state (Eq. 17) and have led to an increase in scattering.

5. Numerical analysis of the sprinkling relationship

Equation 16 shows how the Fermi pressure of the Boehm potential and the Coulomb exchange interaction between particles change the dispersion relation of hydromagnetic waves, the term related to spin appeared in the second term from the right side. As it is clear from Equation 16, the quantum effects caused by the density fluctuations with a positive sign increase the scattering. The effect of spin magnetization and exchange-correlation show a decreasing contribution to the scattering of these waves, unlike the quantum diffraction statements. This issue can be seen in Figure 2, which examines the presence and absence of the spin quantum term (spin magnetization effect). In numerical analysis, numerical parameters related to GaAs semiconductor can be used [30], which are:
$n_0 = 4.7 \times 10^{16}$ cm^{-3}, $T = 10$ K, $V_{Fe} = 1.4 \times 10^5$ cm/s, $\omega_{Pe} = 1.32 \times 10^{13}$ Hz, $B_0 = 10$ μG, $m_e^*/m_e = 0.067$, $m_h^*/m_e = 0.5$.

According to Figure 2, the effect of electron spin magnetization reduces the scattering of hydromagnetic waves.

Studies on the exchange effects in a quantum plasma by considering the spin polarization in the external magnetic field have been done. Since electrons have spin 1/2, therefore, in an external magnetic field, their spin orientation plays an important role in the distribution of particles among quantum states and subsequently creating a new state equation. If the number of fermions with high and low spins is not the same in the presence of an external magnetic field, due to the existence of restrictions on fermion dynamics, which can for example be caused by the effect of the crystal structure of the metal and exchanges between fermions, a spin polarization, is created in the plasma. In addition to creating spin pressure, this polarization is the origin of a completely new quantum Coulomb exchange interaction in plasma, which does not exist in the absence of polarization. The spin polarization of electrons can be caused by the external magnetic field and also related to the effective internal magnetic field in ferromagnetic materials, which generally have a non-zero spin polarization. Since the non-conducting plasma is not a material with ferromagnetic properties, the spin polarization will only be caused by the external field [27, 32].

According to Fig. 1 the studied hydromagnetic waves propagate in the boundary of this plasma in the same direction as

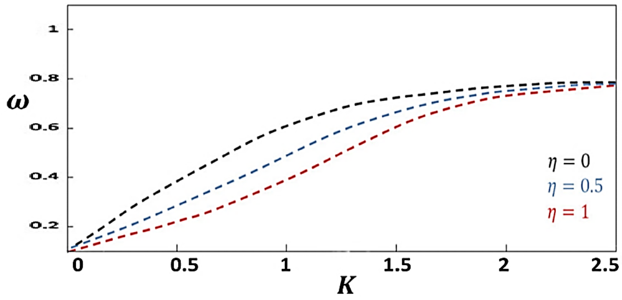

Figure 3. Normalized frequency diagram of hydromagnetic wave (ω) based on normalized wave number (k) for different values of polarizability.

the external magnetic field. In this case, the Lorentz force caused by the magnetic field on the particles is equal to zero, and the effect of the presence of the field appears only in creating spin polarization in the electrons and changing the equation of state of the system.
In Figure 3, the hydromagnetic wave frequency diagram is drawn based on the normalized wave number for different values of polarizability. It is clear in the figure that the role of exchange effects in long wavelengths is much stronger than the Fermi pressure and Boehm potential, therefore it leads to a decrease in the frequency and phase speed of the hydromagnetic wave. Also, with the increase of polarization in the plasma, the speed of the group is also reduced, and as a result, in the presence of this speed, data transmission will be reduced. Also, at short wavelengths, all the curves tend towards 0.7, which is actually the frequency of surface plasma oscillations in a semi-finite plasma. So it can be said that the higher the plasma polarization, the greater the role of the exchange effect, as a result of which the propagation frequency and subsequently the phase speed of hydromagnetic waves decrease. Since the plasmonic coupling parameter is related to quantum effects, the decrease in the value of this parameter means the reduction of the role of exchange effects and Boehm potential. For here, where the coupling parameter $H = 0.5$ is assumed, the role of polarization in the propagation of hydromagnetic waves is not significant, and states with different polarizations and exchange interactions have little differences. On the other hand, the frequency of hydromagnetic wave propagation increases compared to the $\eta = 0$ state, i.e. the absence of exchange interaction and in the presence of Boehm potential, Fermi pressure and exchange potential. As can be seen from Figure 3, this increase in frequency is greater in short wavelengths. In the case of low polarization of 0.2, the role of the exchange effect in long wavelength is greater than the Bohm potential, and the frequency decreases, and on the other hand, as is evident, in the high polarization of 0.5 and 1, the role of the exchange effect is much stronger.

6. Conclusion

In this research, the scattering characteristics of hydromagnetic waves in a semiconductor plasma were studied by considering the quantum corrections affected by the spin of electrons, the total quantum Bohm force and the quantum exchange correlation. The generalized relationship obtained for different states of the plasma environment and angle θ led to scattering relationships related to separate wave modes. The obtained results showed that the quantum correction is caused by the photo enhancement of the density of two types of particles in the perpendicular propagation of order k^4 and has a significant effect on the scattering of these waves. Therefore, the quantum Bohm correction adds a nonlinear part to the scattering relation, which can be important for large k. On the other hand, the spin effect appears in the form of a sentence with factor $(2-\eta^2(\alpha))$ from Equation 16, which is always positive. Therefore, unlike the quantum Bohm potential which increases the scattering of these waves, the spin of electrons and exchange correlation have a reducing effect on the scattering of these waves. On the other hand, quantum effects do not affect the parallel propagation of waves; therefore, for any $\theta = 0$, the spin effect appears in the scattering relation.

Conflict of interest statement:
The authors declare that they have no conflict of interest.

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