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Research Article

Influence of spin on propagation of electromagnetic wave in quantum dusty magnetoplasma

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ABSTRACT

A study of the dispersion of an electromagnetic wave propagating through a uniform quantum dusty plasma under the influence of a transverse magnetic field using the quantum hydrodynamic (QHD) model and taking into account the quantum Fermi pressure, Bohm potential and electron spin. The spatial trajectories of the particles have been obtained for electrons, ions, and dust particles. The inclusion of dust particles is significant as they introduce additional mass and charge effects. Subsequently, the nonlinear current density, comprising the conventional current density and the magnetization current density due to electron spin, has been established. Further, the dispersion relation for electromagnetic waves in quantum dusty plasma has been analyzed. The effects of electron spin have been studied both numerically and analytically. The magnetization current density is significant as it plays a crucial role in accounting for the magnetic interactions and spin effects within the plasma, further influencing the overall dispersion characteristics. The results indicate the influence of spin in quantum dusty plasma increases dispersion, as spin-particle interaction modifies the plasma's collective behavior by increasing Fermi pressure and enhancing propagation velocity.

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INTRODUCTION

The physics of dusty plasmas has attracted a lot of attention since the 1990s [1]. Early 1982s discoveries of unusual characteristics in the Saturnian ring system by the Voyager spacecraft gave it a significant boost [2]. Dust particles, ions, molecules, and electrons are said to make up dusty plasma. In addition, dust particles typically range in size from a few nanometers to tens of micrometers. In actuality, dusty plasma appears not only often in space but also in laboratories and the industrial sector [3-4]. The interactions between charged particles (electrons and ions) and dust particles are the primary focus of dusty plasma research at present, which could be used as a starting point for future investigation of the attenuation characteristic. A plasma with dust particles will be termed as dusty plasma, when a dust particles take part in collective behavior. The plasma dynamics is strongly influenced by the presence of dust grains, which are seen as impurities in the laboratory [5]. This review addresses

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experimental complex plasmas, including their processes, dynamics, and applications [6], while the book explores dusty plasmas' collective processes, such as dust charging and instabilities, from a theoretical perspective [7].

The quantum plasma has attracted a lot of curiosity in the recent years because of its applications in X-ray FEL [8], this review covering theoretical aspects like nonlinear wave interactions, quantum turbulence, and phase-space kinetic structures [9], Recent advancements in laser-produced plasmas for extreme ultraviolet (EUV) and soft x-ray radiation highlight that conversion efficiency is affected by opacity, ion density, and laser wavelength, with ongoing improvements in efficiency and plasma modeling discussed [10], dense astrophysical plasma systems like white dwarfs, neutron stars, core of big planets etc. [11–12], a quantum dot is used to illustrate a semiclassical method for describing a one-dimensional system of interacting electrons [13], and ultra-small electronics devices. Such plasmas are studied mostly using the quantum hydrodynamic model [14]. For the study of numerous collective effects involving various quantum forces, the QHD equations are helpful [15]. The propagation of linear waves in a homogeneous cold quantum plasma with a quasi-external magnetic field has been studied by Ren et al. [16–17]. It has been studied how, in a homogeneous quantum plasma, electrostatic perturbations in ion-acoustic density of small but finite amplitude impact the nonlinear propagation of electromagnetic electron-cyclotron waves along an external magnetic field. It takes into consideration the combined effects of the classical and spin-induced ponderomotive forces along with the quantum force related to the Bohm potential, respectively [18]. P. K. Shukla studied the linear dispersion relation while taking account of the quantum Bohm potential and the 1/2-electron spin effect using the propagation of electromagnetic waves that are elliptically polarized in a dense quantum system [19]. Recent studies have focused on understanding the influence of spin magnetization on instability criteria and MHD wave properties in degenerate plasma environments like white dwarfs and neutron stars [20]. Moreover, investigations have shown that Coulomb exchange effects and spin polarization can elevate the frequency of surface plasma waves (SPW) and enhance optical gain during stimulated emission, emphasizing their substantial role in semiconductor quantum plasma dynamics [21].

When a dusty plasma is sufficiently cooled, reaching a temperature at which the inter particle distance approaches the de-Broglie wavelengths, it assumes significant importance in the study of quantum phenomena. At this temperature, dusty plasma acts like a Fermi gas and it is considered that quantum mechanical effects will have a significant impact on how charged dust particles behave. Quantum dusty plasma has been the subject of several studies during the past decade. Numerous quantum effects of various kinds have recently been observed in dusty plasma [22-25]. This study explores the theoretical characteristics of dust magnetosonic (DMS) solitons within a magnetized plasma framework comprising inertialess ions, electrons, and negatively charged warm dust grains. It aims to deepen understanding of how these components interact to form and sustain DMS solitons in complex plasma environments [26].

Microelectronic devices and metallic nanostructures are vulnerable to contamination by highly charged impurities, leading to the formation of a quantum dusty plasma. Whether introduced artificially or through natural processes, such impurities, often ions or charged particles, disrupt the materials' electronic properties. This disturbance triggers the creation of a dusty plasma, where charged particles and solid impurities coexist within a plasma medium. Quantum effects, especially pronounced at the nanoscale, amplify the impact of impurities on the electronic behavior of the material. Whether arising from fabrication processes or environmental exposure, the presence of highly charged impurities necessitates careful consideration for rthe design and operation of these structures, highlighting the importance of mitigation strategies in ensuring optimal performance [27]. In a few cosmic objects, Reach et al. [28] found some indications of degenerate dusty plasmas. In accordance to their research, clouds of dust (photospheric metals) which could pollute the surfaces of white dwarfs (WDs) exist surrounding these. They utilized the Spitzer Space Telescope to study the emission spectra of many different substances (which includes amorphous carbon, crystalline enstatite, silicates, and forsterites) in WDs, consequently validating their hypothesis that dust grains are present in dense plasmas. The identification of dust particles in WDs, makes one conclude that WD's has characteristics comparable to a thick solid with deficient electrons within an ion lattice possibly containing more heavy particles [29–30]. Recent studies of neutron star (NS) dust particles were carried out by Omand et al. [31]. It is found that the inside of NS has a large atomic nucleus with interacting nucleons, electrons, possibly additional large elementary particles and condensates. The cosmic medium that shields these extreme situations from gravitational collapse endured enormous compaction. In addition to NS[32], dust is seen in other very magnetic dense objects including as supernovae, supernova remnants, and young star objects. Other extremely magnetic dense objects, such as supernovae, supernova remnants, and young star objects, in addition to NS, exhibit dust. The most recent astrophysical refers to of dust are the nonlinear excitation of gravitational waves [33], Quantum electro dynamic effects in stellar shock propagation and infrared studies for dust recognition in between stellar remains are a couple examples [34-35].

One of the most significant aspects of evolution of the intrinsic spin of electron is that it can persist even when macroscopic variations take place on scales larger than the thermal de Broglie wavelength, which is considered as classical scale. The spin effect in plasma is discovered to be slightly different from those of the non-spin quantum effect in plasma for high temperature plasma due to quantum characteristic caused by the intrinsic magnetic moment of the electron. Numerous publications have been published during the past decade regarding the way of the spin -1/2 effect affects plasma dynamics. In recent research, S. Singh examined the ponderomotive effect in high-density quantum plasma under an axial magnetic field, incorporating Fermi pressure, Bohm potential, and spin–spin exchange interactions during laser pulse propagation [36]. Furthermore, the investigation into the influence of spin-up and spin-down exchange interactions on electron acceleration by a surface plasma wave (SPW) in magnetized quantum plasma has been a focus of study [37]. These efforts contribute to our understanding of complex plasma dynamics influenced by magnetic fields and exchange interactions. Due to its applicability in industry and space exploration, dense quantum dusty plasmas a promise an expanding field in near future [38-40].

In this paper, we present a theoretical analysis of spin in dispersion when a linearly polarized electromagnetic wave passes through a uniform quantum dusty plasma acted upon by a magnetic field transversely. The dispersion relation due to the spin effect in the quantum dust plasma is presented in Section 3. Conclusions are given in Section 4.

FORMULATION

We consider a high density quantum plasma with three constituents: electrons, ions, and dust particles. The criteria for charged neutrality has been satisfied at equilibrium. i.e $n_{io} = n_{eo} + q_d\, n_{do}$; The ions, electrons, and dust particles respective densities are shown here as n_{eo} , n_{io} and n_{do}. The charge that is present on each dust particle can be expressed as $q_d = z_d\, e$, where z_d is the dust grain's charge number and e being the charge on each electron.

The linearly polarized e. m. wave propagates along z-direction acted upon by a constant magnetic field $\vec{B}_0 = b\hat{y}$. The electric field of the plane wave is given by,

$$\vec{E} = \vec{E}_0 e^{i(kz-\omega t)} \quad (1)$$

The electromagnetic field and plasma's interaction is governed by the QHD equations, which are [18, 41,42]:

$$\frac{d\vec{v}_e}{dt} = -\frac{e}{m_e}\vec{E} - \frac{e}{m_e c}(\vec{v}_e \times \vec{B}) - \frac{\vec{v}_F^2}{3n_0}\frac{\nabla n^3}{n} + \frac{\hbar^2}{2m_e}\nabla\left(\frac{1}{\sqrt{n}}\nabla^2\sqrt{n}\right) - \frac{2\mu}{m_e\hbar}\vec{S}.\left(\nabla\vec{B}\right) \quad (2)$$

$$\frac{d\vec{v}_i}{dt} = \frac{e}{m_i}\vec{E} + \frac{e}{m_i c}(\vec{v}_i \times \vec{B}) - \frac{\vec{v}_F^2}{3n_0}\frac{\nabla n^3}{n} + \frac{\hbar^2}{2m_i}\nabla\left(\frac{1}{\sqrt{n}}\nabla^2\sqrt{n}\right) \quad (3)$$

$$\frac{d\vec{v}_d}{dt} = \frac{q_d}{m_d}\vec{E} + \frac{q_d}{m_d c}(\vec{v}_d \times \vec{B}) \quad (4)$$

$$\left(\frac{\partial}{\partial t} + \vec{v}.\nabla\right)\vec{S} = \frac{2\mu_B}{\hbar}\left(\vec{B}\times\vec{S}\right) \quad (5)$$

where, me, mi and md are mass of electron, ion and dust particles respectively, n_0 and $n(= n + n^{(1)})$ are ambient and total plasma densities, $v_F = (\hbar/m)(3\pi^2 n)^{1/3}$ is the Fermi velocity and $\vec{S}$ is the spin angular momentum with $|S| = |S_0| = \hbar/2$, $\mu = (-g/2)\mu_B$ where g = 2.0023193 and $\mu_B = e\hbar/2m$ is the Bohr magneton. Equation (2)'s first component on the RHS is the Lorentz force, while the second component signifies the force caused by Fermi electron pressure. $\left(P_F = m v_F^2 n^3/3n_0^3\right)$, The third part gives the quantum Bohm potential's force, which results from quantum corrections to density fluctuation, and the last term shows the spin magnetic moment of electron. The quantum effects are insignificant in ions and dust dynamics due to inertia (high mass) there by having smaller de-Broglie wave length. The many spin states are well represented by a macroscopic average, equation (2) above remains applicable. In the limit of $\hbar = 0$, the classical equations may be recovered [43].

The first order transverse and longitudinal velocities of the plasma species are given by perturbatively expanding equations (2) - (4) for the first order fields and substituting all the necessary variables,

$$v_{xe}^{(1)} = \frac{\Omega_{xe}}{\left(\omega^2 - \omega_{ce}^2\right)} e^{i(kz-\omega t)}; \qquad v_{ze}^{(1)} = \frac{\Omega_{ze}}{\left(\omega^2 - \omega_{ce}^2\right)} e^{i(kz-\omega t)}$$

$$v_{xi}^{(1)} = \frac{\Omega_{xi}}{\left(\omega^2 - \omega_{ci}^2\right)} e^{i(kz-\omega t)}; \qquad v_{zi}^{(1)} = \frac{\Omega_{zi}}{\left(\omega^2 - \omega_{ci}^2\right)} e^{i(kz-\omega t)}$$

$$v_{xd}^{(1)} = \frac{\Omega_{xd}}{\left(\omega^2 - \omega_{cd}^2\right)} e^{i(kz-\omega t)}; \qquad v_{zd}^{(1)} = \frac{\Omega_{zd}}{\left(\omega^2 - \omega_{cd}^2\right)} e^{i(kz-\omega t)}$$

where,

$$\Omega_{xe} = -ica_e\omega^2 + (\omega + i\omega_{ce})\left(v_F^2 + \frac{\hbar^2}{4m^2}\right)k + \frac{2a_e mc\mu_B S k^2}{em\hbar}(-\omega + i\omega_c),$$

$$\Omega_{xi} = -ica_i\omega^2 + (\omega + i\omega_{ci})\left(v_F^2 + \frac{\hbar^2}{4m^2}\right)k,$$

$$\Omega_{xd} = -ica_d\omega^2,$$

$$\Omega_{ze} = -ica_e\omega_{ce}\omega + (\omega - i\omega_{ce})\left(v_F^2 + \frac{\hbar^2}{4m^2}\right)k + \frac{2a_e mc\mu_B S\omega_c k^2}{e}(1+\omega),$$

$$\Omega_{zi} = ica_i\omega_{ci}\omega + (\omega - i\omega_{ce})v_F^2 k,$$

and

$$\Omega_{zd} = ica_d\omega_{cd}\omega.$$

The dispersion properties of the radiation field are not affected by external magnetic field in the lowest order. $a_e = eE_0/m_e c\omega$, $a_i = eE_0/m_i c\omega$ and $a_d = q_d E_0/m_d c\omega$ are the normalized amplitudes with $\omega_{ce} = eE_0/m_e\, c$, $\omega_{ci} = eE_0/m_i\, c$ and $\omega_{cd} = eE_0/m_d\, c$ being cyclotron frequencies respectively.

On perturbatively expanding equation (5) for the first order fields and substituting the appropriate terms, it is found that the first order longitudinal and transverse spin angular momentum are

$$S_x^{(1)} = \frac{(2\mu/\hbar)S_0 ka\alpha}{\left(\omega^2 - \omega_s^2\right)} e^{i(kz-\omega t)} \tag{6}$$

$$S_z^{(1)} = \frac{(2\mu/\hbar)S_0 ka\alpha^*}{\left(\omega^2 - \omega_s^2\right)} e^{i(kz-\omega t)} \tag{7}$$

where,

$$\omega_s = \frac{2\mu b_0}{\hbar}, \qquad \alpha = i\frac{mc\omega}{2e} + \frac{2\mu}{\hbar}\frac{m^2c^2\omega_c k^2}{2e^2},$$

and * denotes the complex conjugate.

Dispersion Relation

The transverse current density is the result of adding the source current $\vec{J}_c\left(= -en\vec{v}\right)$ with the current density derived due the spin magnetic moment $\vec{J}_S\left(= \frac{2\mu}{\hbar}\nabla.n\vec{S}\right)$,

$$\vec{J} = \vec{J}_C + \vec{J}_S = \left(\frac{n_{oi}e\Omega_{zi}}{\omega^2 - \omega_{ci}^2} - \frac{n_{oe}e\Omega_{ze}}{\omega^2 - \omega_{ce}^2} - \frac{q_d n_{od}\Omega_{zd}}{\omega^2 - \omega_{cd}^2} + i\frac{4\omega\mu_B^2}{\hbar^2}\frac{Sk\alpha\alpha^*}{\omega^2 - \omega_s^2}\right)e^{i(kz-\omega t)} \tag{8}$$

The following wave equation explains how a laser pulse propagate with plasma

$$\left(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right)\vec{E} = \frac{4\pi}{c^2}\frac{d\vec{J}}{dt}. \tag{9}$$

The dispersion relation is obtained by substituting the current density from equation (8)

$$c^2k^2 = \omega^2 + \frac{\omega_{pe}^2\Lambda_e}{\left(\omega^2 - \omega_{ce}^2\right)} + \frac{\omega_{pi}^2\Lambda_i}{\left(\omega^2 - \omega_{ci}^2\right)} + \frac{\omega_{pd}^2\Lambda_d}{\left(\omega^2 - \omega_{cd}^2\right)} + \frac{\Lambda_s}{\left(\omega^2 - \omega_s^2\right)} \tag{10}$$

where,

$$\Lambda_e = \omega\omega_{ce} + i(\omega - \omega_{ce})\left(v_F^2 + \frac{\hbar^2}{4m^2}\right)k + i\left(\frac{(2am\mu_B S\omega_0 k^2)(1+\omega)}{a_e}\right),$$

$$\Lambda_i = \omega\omega_{ci} + \frac{i(\omega - \omega_{ci})v_F^2 k}{a_i c},$$

$$\Lambda_d = \omega\omega_{cd}$$

and

$$\Lambda_s = \frac{16\pi e\mu_B^2\omega sk\alpha\alpha^*}{mc\hbar^2}.$$

The terms $\left(\omega^2 - \omega_{ce}^2\right)$, $\left(\omega^2 - \omega_{ci}^2\right)$, $\left(\omega^2 - \omega_{cd}^2\right)$ and $\left(\omega^2 - \omega_s^2\right)$ are of the same order of magnitude, and this enables both the continuous magnetic field and the radiation's magnetic component, also have similar order. In the limits, $\omega^2 < \omega_{ci}^2 < \omega_{cd}^2$ and $m_e < m_i < m_d$: the above dispersion relation reduces to the classical result [36]. The numerical analysis has been carried out for parameter applicable to the interiors of the neutrons stars, the magneters and white dwarfs [37-39]. These parameters are given in the CGS units $c = 3\times10^{10}$; $m_e = 9.1\times10^{-28}$; $m_i = 1.65\times10^{-24}$; $m_d = 10^8 m_i$; $e = 4.8\times10^{10}$; $h = 1.05\times10^{-27}$; $k_B = 1.38\times10^{-16}$; $n_{eo} = 1\times10^{27}$; $n_{io} = 1.001\times10^{27}$; $n_{do} = 10^{-4}n_{io}$; $z_{do} = \frac{n_{io} - n_{eo}}{n_{do}}$; $q_d = z_{d0}e = 4.8\times10^{11}$; $B_0 = 10^6 - 10^8$; and $T_i = 10^8$[43-45].

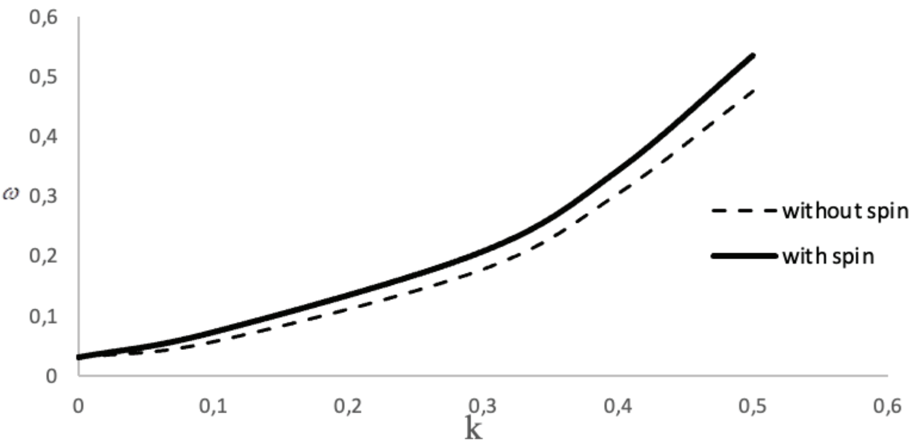

Figure 1. Variation of ω with k for $m_e = 9.1\times10^{-28}$, $m_i = 1.65\times10^{-24}$, $m_d = 10^8 m_i$, $e = 4.8\times10^{10}$, $n_{eo} = 1\times10^{27}$, $n_{io} = 1.001\times10^{27}$, $n_{do} = 10^{-4}n_{io}$, $q_d = 4.8\times10^{-13}$, $\omega_c/\omega = 0.3$. The dashed line and solid line show the variation without spin and with spin consideration of electron respectively.

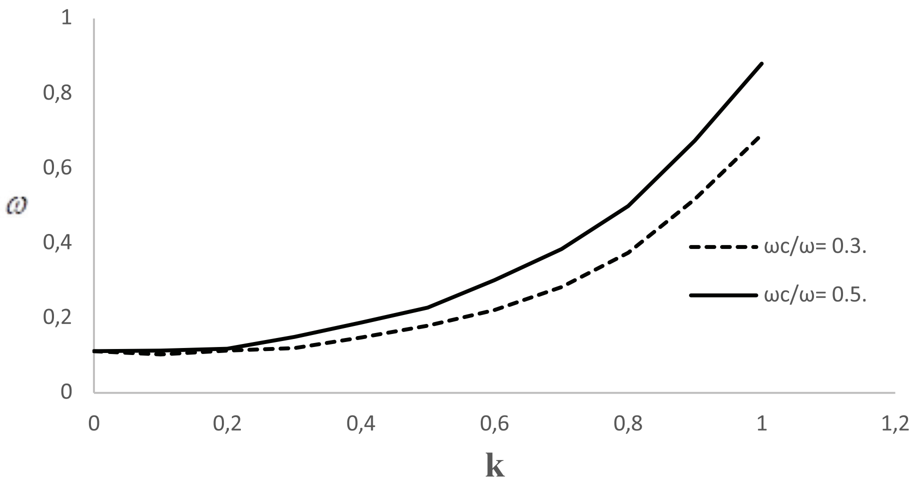

Figure 2. Variation of ω with k for $m_e = 9.1\times10^{-28}$, $m_i = 1.65\times10^{-24}$, $m_d = 10^8 m_i$, $e = 4.8\times10^{10}$, $n_{eo} = 1\times10^{27}$, $n_{io} = 1.001\times10^{27}$, $n_{do} = 10^{-4} n_{io}$, $q_d = 4.8\times10^{-13}$. The dashed line and solid line represents for $\omega_c / \omega = 0.3$ and $\omega_c / \omega = 0.5$ respectively.

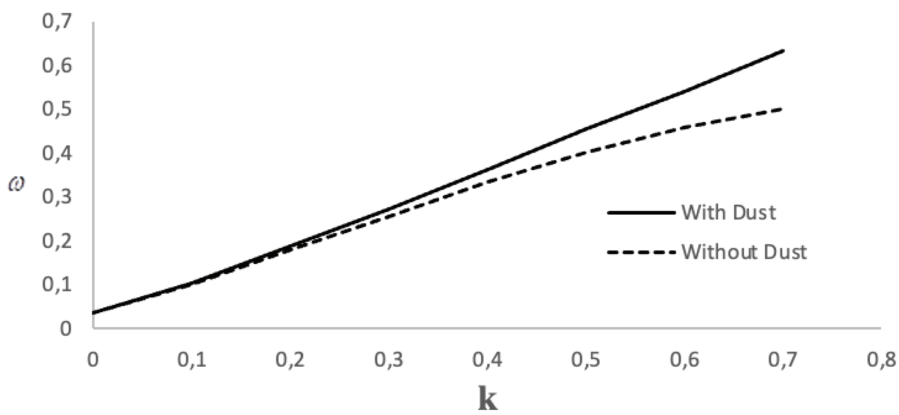

Figure 3. Variation of ω with k for $m_e = 9.1\times10^{-28}$, $m_i = 1.65\times10^{-24}$, $m_d = 10^8 m_i$, $e = 4.8\times10^{10}$, $n_{eo} = 1\times10^{27}$, $n_{io} = 1.001\times10^{27}$, $n_{do} = 10^{-4} n_{io}$, $q_d = 4.8\times10^{-13}$ and $\omega_c / \omega = 0.3$. The dashed line and solid line represents for without dust and with dust respectively.

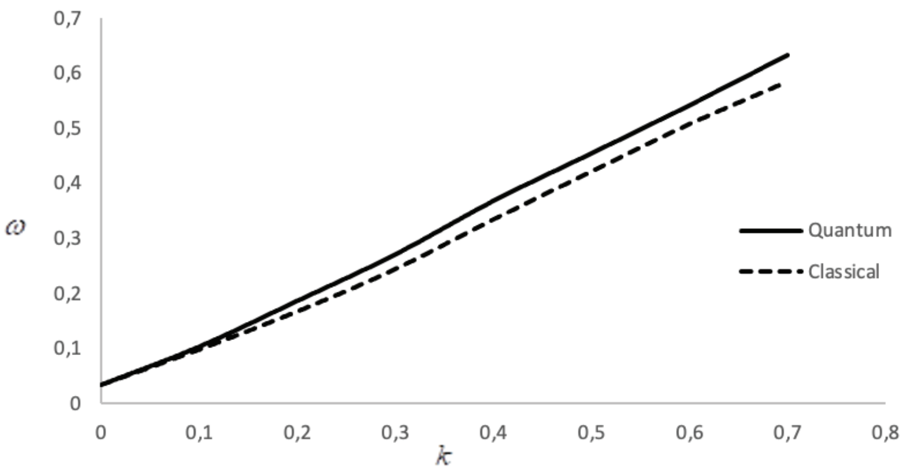

Figure 4. Variation of ω with k for $m_e = 9.1\times10^{-28}$, $m_i = 1.65\times10^{-24}$, $m_d = 10^8 m_i$, $e = 4.8\times10^{10}$, $n_{eo} = 1\times10^{27}$, $n_{io} = 1.001\times10^{27}$, $n_{do} = 10^{-4} n_{io}$, $q_d = 4.8\times10^{-13}$ and $\omega_c / \omega = 0.3$. The dashed line and solid line represents for classical and quantum dusty plasma respectively.

Figure 1 presents the variation of angular frequency (ω) with wave number (k) for $\omega_c / \omega = 0.3$. The solid line shows the growth considering the electron spin while the dashed line shows the growth in absence of spin consideration. Thus, the electron spin contributes to dispersion elevates the growth by nearly 12%. This is due to the enhanced collective behaviors of particles under the influence of spin effects.

Figure 2, shows the curves of dispersion where it is observed that ω increases with k and ω_c. Initially, the frequency increases slowly with k but the rate increases with further increase in k.

Figure 3, the dispersion characteristics of both quantum plasma and quantum dusty plasma are presented. The dust reduces, the growth of about 7%. This decrease can be attributed to the higher mass of dust particles relative to electrons and ions. The difference in mass alters the collective behavior of the plasma waves, leading to reduced dispersion.

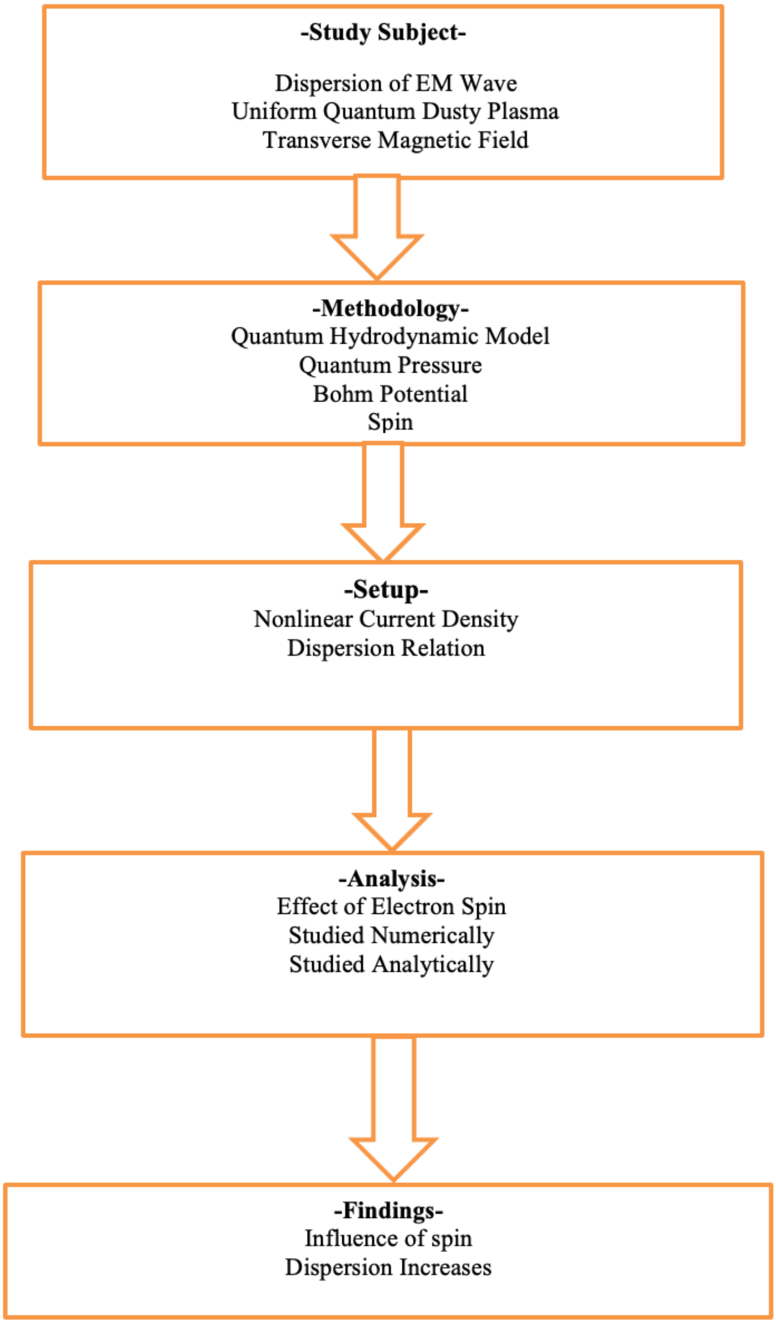

Figure 5. Block diagram

To compare the quantum dusty plasma results with the classical dusty plasma, the dispersion has been plotted in Figure 4. For similar parameters, the solid line shows the variation for quantum dusty plasma and the dashed line shows the variation in classical dusty plasma. It is observed that quantum effects contributed to growth by about 10%. This increase is attributed to Bohm potential promoting particle spread, Fermi pressure preventing particle closeness, spin altering particle interactions and trajectories and dust grains introducing extra interaction and collective behaviors, collectively enhancing dispersion in quantum dusty plasma (Fig. 5).

CONCLUSION

In this paper, we have developed a theoretical formalism to investigate the influence of spin in magnetized quantum dusty plasma. Our formalism incorporates various quantum effects such as Fermi pressure, Bohm potential and electron spin while deriving the dispersion equation using the quantum hydrodynamic (QHD) model. We have analyzed the dispersion of a linearly polarized e. m. wave in quantum dusty magnetoplasma taking into the spin effects. The results indicates a notable increase in dispersion in the presence of electron spin, with spin contributing to a growth of about 12%. This occurs by a higher Fermi pressure, which is affected by the electron's spin magnetic moment, which is essential in the presence of a magnetic field. The enhancement in the propagation velocity due to spin also contributes to growth. The results will be useful may useful in study of White dwarf and Neutron star interiors [43-45] and future generation high density plasma experiments.

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

STATEMENT ON THE USE OF ARTIFICIAL INTELLIGENCE

Artificial intelligence was not used in the preparation of the article.

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