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Energy transport for ion acoustic waves in a spin polarized quantum plasma

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Abstract

The separate spin evolution quantum hydrodynamics (SSE-QHD) model is used to investigate the energy behavior for ion acoustic waves in degenerate quantum plasma. Numerical results show that the energy flow speed decreases with spin polarization parameter. It is also shown that it decreases with the increasing rate up to a certain range of wave number and then it goes to zero asymtotically. It is observed that Bohm potential suppresses the energy flow speed. It is also noticed that the energy flow speed deviates from the group velocity even in the absence of Bohm potential effect. However, the contribution of of Bohm poential effect in spin polarized plasma reduces the extent of deviation.

Keywords: spin polarization, quantum plasma, ion acoustic wave, energy flow speed

(Some figures may appear in colour only in the online journal)

1. Introduction

In the last two decades, theoretical plasma physicists extensively studied quantum plasma which has several applications both in laboratory plasma (in microelectronic devices, laser produced plasma, nano-systems) [1–3] and in astrophysical environments like extremely dense systems (e.g. interior of the Jovian planets, white and brown dwarfs, neutron stars, pulsars and magnetars) [4, 5]. The overdense plasmas, in which the Fermi temperature is higher than the thermal temperature, require the quantum treatment for their description. The quantum statistical effects are included through the Fermi degenerate pressure. In such systems the de Broglie wavelength exceeds the inter-particle distance and thus the pure quantum interactions result into the diffraction and tunneling effects which are taken into account by including the Bohm potential term in the momentum equation. The spin is an intrinsic property of fundamental particles. The charge particles behave like tiny magnetic dipoles. In the presence of external magnetic field, these magnetic dipoles get oriented which leads to interactions among the electrons. The quantum hydrodynamic (QHD) model and quantum kinetic model have been developed for the description of spin-$1/2$ quantum plasmas in [6–10]. Using these models various linear and nonlinear wave phenomena have been discussed for both the classical and degenerate plasmas [11–16]. The electronic structure in matter is governed by the electron spin. The spin polarization plays a fundamental role for functioning of spintronic devices and magnetoelectronic devices. In the magnetically ordered metals (like Fe, Co, Ni, or MnAs), used in developing spintronic devices, the electron gas is spin polarized [17]. A spin-polarized plasma also occurs in semiconductor plasma [18] which has beenr verified experimentally in [19]. Recently, highly intense laser pulses have been employed to produce a high degree of spin polarization in electron gas. Furthermore, it is well known that the concept of spin-polarized electrons is used to study particle physics as well as electron spectroscopy [20]. It has also been found using traditional hydrodynamics and kinetic set of equations that the spin polarization of electrons changes significantly the properties of the collective excitations like Langmuir and zero sound waves produced in degenerate semiconductor plasma. Additionally, it has been noticed that the spin polarization reduces the decelerating ability of a plasma [21]. Inastrophysical environments where the magnetic field is sufficiently strong a spin polarized electron gas is produced [22]. Now it is well established that the study of spin polarization effect is important in both the laboratory and astrophysical environments.

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Recently, another QHD model for spin-$1/2$ particles has been proposed by Andreev [23] based on separate spin evolution. According to this model, electrons are assumed to form two separate fluids comprising of spin-up electrons and spin-down electrons. Therefore, on the basis of the separate spin, such a model is termed as separated spin evolution quantum hydrodynamic (SSE-QHD) model. This model has recently attracted the attention of researchers because it not only modifies the linear and nonlinear properties of plasma waves but also gives birth to new wave solutions and nonlinear structures in the degenerate magnetized plasma [23–30] . For instance SSE gives the existence of spin electron acoustic wave which is useful to explain the phenomenon of high temperature superconductivity in the magnetically ordered mediums [31]. Recently using SSE-QHD model the oblique propagation of electromagnetic waves has been studied for spin polarized plasma and it was found that SSE gives two new spin dependent obliquely propagating waves in the spectrum of the earlier reported electromagnetic waves [32]. The effect of spin polarization on growth rate of various electrostatic and electromagnetic instabilities has been discussed in [33–39].

Recently, several authors have shown interest in the study of energy transport of various waves in quantum plasma. The energy transport speed is found by taking the overall energy flux density divided by total stored energy density. As we know different types of energy may be involved in the transport phenomenon in a wave [40, 41]. In case of electromagnetic waves, Poynting theorem relates the energy flow rate with the time rate of energy density [42]. This theorem has also been used for energy transport by electrostatic wave [43]. It is obvious that energy transferred by an electrostatic wave in a quantum plasma is shared by the electric potential energy and quantum interaction energy. Currently, a number of works on this subject have been done for electrostatic and electromagnetic waves for electron-ion, magnetized/unmagnetized quantum Fermi plasmas [44, 45]. In these works the energy densities and energy flow speed for both the electrostatic and electromagnetic waves have been investigated in quantum plasma in which only Bohm potential effect was taken into account. It is obvious that spin of the electrons causes their mutual interactions in the presence of external magnetic field. Consequently, the overall energy density is also shared by the spin interaction energy and hence the energy flow speed is modified. Therefore, it is important to include the electron spin effect in the study of energy behavior. Ion acoustic wave is one of the fundamental mode in plasma which is equally important in both the space and laboratory environments. An important aspect of energy transport through the ion acoustic wave has not yet been studied for the spin-$1/2$ degenerate quantum plasma. In this manuscript, we discuss the energy densities and energy flow speed for low frequency ion wave in a magnetized electron-ion quantum degenerate plasmas on the basis of SSE.

The manuscript is ordered as follows: in section 2, the mathematical formalism for the derivation of different energy densities and energy flow speed for ion acoustic wave is presented. Results and discussion are given in section 3. Section 4 is devoted for the summary and conclusion.

2. Mathematical formalism

For the study of energy behavior for the low frequency ion wave in a spin polarized plasma, first of all, we work out the dispersion relation. We consider an electron-ion plasma with an ambient magnetic field along the z-axis. In order to include the dynamics of bulk electrons, we use the SSE-QHD equations [23] which are developed in the presence of external magnetic field for each of the species with spin-up and spin-down by considering them as separate fluids. The discontinuity equation due to the spin projection of each specie is presented as

$$\partial_t n_{es} + \nabla \cdot (n_{es} \boldsymbol{v}_{es}) = (-1)^{i_s} T_{ez}, \tag{1}$$

where $s = u,\ d$ denotes the spin-up and spin-down state of electrons, n_{es} and $\boldsymbol{v}_{es}$ are the electron number density and their velocity being in the spin state s, $T_{ez} = \frac{\gamma_e}{\hbar}(B_x S_{ey} - B_y S_{ex})$ is the z-projection of spin torque, $\gamma_e = -\mu_B$, where μ_B is the Bohr magneton, i_s: $i_u = 2$, $i_d = 1$, with the spin density projections S_{ex} and S_{ey}, each representing the evolution of the spin-up and spin-down states of electrons. Therefore, the functions S_{ex} and S_{ey} need not to have subindices u and d. In this model, the z-projection of the spin density S_{ez} is not an independent variable, it is the function of difference in number densities of spin-up and spin-down electrons i.e. $S_{ez} = n_{eu} - n_{ed}$. Normally the right hand side of the continuity equation is zero which shows the conservation of the particle number. If we treat the spin-up electrons and the spin-down electrons as different fluids, we see that the particle numbers change due to the spin interaction. However, the total number of the particles conserves i.e. $n = n_u + n_d$. The equation of motion for electron species is given as

$$\begin{aligned} &m_e n_{es}(\partial_t + \boldsymbol{v}_{es} \cdot \nabla)\boldsymbol{v}_{es} + \nabla P_{Fes} \\ &\quad - \frac{1}{9}\frac{\hbar^2}{4m_e} n_{es} \nabla\left(\frac{\Delta n_{es}}{n_{es}} - \frac{(\nabla n_{es})^2}{2n_{es}^2}\right) \\ &= -e n_{es}\left(\boldsymbol{E} + \frac{1}{c}[\boldsymbol{v}_{es}, \boldsymbol{B}]\right) + (-1)^{i_s}\gamma_e n_{es} \nabla B_z \\ &\quad + \frac{\gamma_e}{2}(S_{ex}\nabla B_x + S_{ey}\nabla B_y) \\ &\quad + (-1)^{i_s} m(\widetilde{\boldsymbol{T}}_{ez} - \boldsymbol{v}_{es} T_{ez}), \end{aligned} \tag{2}$$

where $P_{es} = (6\pi^2)^{2/3} n_{es}^{5/3}\hbar^2/5m$ is the degenerate pressure for spin-up and spin-down electron fluids, $\hbar^2$-term is the Bohm potential, the number $1/9$ appears in the front of Bohm term for three dimensions and the low-frequency waves [46] $\widetilde{\boldsymbol{T}}_{ez} = \frac{\gamma_e}{\hbar}(\boldsymbol{J}_{(M)ex} B_y - \boldsymbol{J}_{(M)ey} B_x)$ represents the torque current, where $\boldsymbol{J}_{(M)ex} = (\boldsymbol{v}_{eu} + \boldsymbol{v}_{ed}) S_{ex}/2$, and $\boldsymbol{J}_{(M)ey} = (\boldsymbol{v}_{eu} + \boldsymbol{v}_{ed}) S_{ey}/2$ are the convective parts of the spin current tensor. We suppose that the ions are cold, unmagnetized and classical due to their larger mass. The momentum and continuity equations for ions are, respectively, expressed as

$$m_i \frac{\partial \boldsymbol{v}_i}{\partial t} = Ze\boldsymbol{E}, \tag{3}$$

$$\frac{\partial n_i}{\partial t} + \nabla \cdot (n_i \boldsymbol{v}_i) = 0. \tag{4}$$

The Gauss's law of electrostatics, which connects the perturbation in charge density to the electric field, is written as

$$\nabla.\mathbf{E} = \frac{e}{\epsilon_0}(n_i - n_{eu} - n_{ed}). \tag{5}$$

We assume plane wave solution for all the perturbed quantities $(n, v, E) \sim e^{i(kz-\omega t)}$ in equations (1)–(4) and by using relationship $E_z = -ik\Phi$ we obtain the relations for the perturbed velocity and number density of bulk spin-up, spin-down electrons, and ions as given by

$$v_{1es} = -\frac{e\omega k\Phi}{m_e\left(\omega^2 - k^2 v_{Fes}^2 - \frac{\hbar^2 k^4}{4m_e^2}\right)}, \tag{6}$$

$$n_{1es} = -\frac{en_{e0s}k^2\Phi}{m_e\left(\omega^2 - k^2 v_{Fes}^2 - \frac{\hbar^2 k^4}{4m_e^2}\right)}, \tag{7}$$

$$v_{1i} = \frac{Zek\Phi}{m_i\omega}, \tag{8}$$

$$n_{1i} = \frac{Zen_{i0}k^2\Phi}{m_i\omega^2}. \tag{9}$$

Now by using equations (7) and (9) in (5) we get the dispersion relation for ion acoustic wave with spin polarization effect as

$$\omega^2 = \frac{\omega_{pi}^2\left(v_{Feu}^2 + \frac{1}{9}\frac{\hbar^2k^2}{4m^2}\right)\left(v_{Fed}^2 + \frac{1}{9}\frac{\hbar^2k^2}{4m^2}\right)k^2}{\left(v_{Feu}^2 + \frac{1}{9}\frac{\hbar^2k^2}{4m^2}\right)\left(v_{Fed}^2 + \frac{1}{9}\frac{\hbar^2k^2}{4m^2}\right)k^2 + \omega_{peu}^2\left(v_{Fed}^2 + \frac{1}{9}\frac{\hbar^2k^2}{4m^2}\right) + \omega_{ped}^2\left(v_{Feu}^2 + \frac{1}{9}\frac{\hbar^2k^2}{4m^2}\right)}. \tag{10}$$

Here $\omega_{pe(u,d)}^2 = (1 \mp \eta)\omega_{pe}^2/2$, where ω_{pe} is the usual electron plasma frequency, $v_{F_{e(u,d)}}^2 = v_{F_e}^2(1 \mp \eta)^{\frac{2}{3}}/3$, $v_{Fe} = (3\pi^2 n_{e0})^{1/3}\hbar/m_e$ is the ordinary Fermi velocity of electrons. The spin polarization parameter is defined by $\eta = (n_{e0u} - n_{e0d})/n_{e0} = -(3\mu_B B_0/2\varepsilon_{F_e})$, where $\varepsilon_{F_e} = (3\pi^2 n_{e0})^{2/3}\hbar^2/2m_e$ is the Fermi energy of the electrons. The equilibrium number densities of spin-up and spin-down electrons can be expressed as $n_{e0(u,d)} = n_{e0}(1 \mp \eta)/2$ where n_{e0} is the the total electron number density. The group velocity of the ion acoustic wave is obtained from equation (10) as

$$v_g = \frac{\frac{\omega_{pi}}{k^3}\left[\sum_{s=u,d}\frac{\omega_{pes}^2\left(v_{Fes}^2 + \frac{2}{9}\frac{\hbar^2k^2}{4m^2}\right)}{\left(v_{Fes}^2 + \frac{1}{9}\frac{\hbar^2k^2}{4m^2}\right)^2}\right]}{\left[1 + \sum_{s=u,d}\frac{\omega_{pes}^2}{\left(v_{Fes}^2 + \frac{1}{9}\frac{\hbar^2k^2}{4m^2}\right)k^2}\right]^{\frac{3}{2}}}. \tag{11}$$

The Poynting theorem can be expressed within the electrostatic framework as follows,

$$\frac{\partial\Gamma}{\partial z} = -\frac{\partial}{\partial t}\left(\frac{1}{2}\epsilon_0 E_z^2\right) - E_z J_z, \tag{12}$$

where Γ is the energy flux density and $J_z = e(Zn_{i0}v_{zi} - n_{e0u}v_{zu} - n_{e0d}v_{zd})$ is the current density. We use equations (2), (6)–(9) to obtain $E_z J_z$,

$$E_z J_z = \sum_{s=u,d}\left(\frac{m_e n_{e0s}}{2}\frac{\partial v_{zes}^2}{\partial t} + \frac{m_e\left(v_{F_{es}}^2 + \frac{\hbar^2k^2}{4m_e^2}\right)}{2n_{e0(u,d)}}\frac{\partial n_{es}^2}{\partial t} + m_e\left(v_{Fes}^2 + \frac{\hbar^2k^2}{4m_e^2}\right)\frac{\partial(n_{es}v_{zes})}{\partial z}\right) + \frac{m_i n_{i0}}{2}\frac{\partial v_{zi}^2}{\partial t}. \tag{13}$$

We assume that $\Phi = \Phi_0\cos(kz - \omega t)$. Now we use equations (6)–(10) to express the energy conservation law as follows

$$\frac{\partial\Gamma}{\partial z} + \frac{\partial\varepsilon}{\partial t} = 0, \tag{14}$$

where $\Gamma = \Gamma_{zE} + \Gamma_{zQ}$ and $\varepsilon = \varepsilon_E + \varepsilon_K + \varepsilon_Q$. Here the subscripts E, K and Q represent the electric, kinetic and quantum contribution in the energy. We can easily identify the different contributions in energy density and energy flow density from the energy conservation law equation (14):

$$\varepsilon_E = \frac{1}{2}\epsilon_0 k^2\Phi_0^2\sin^2(kx - \omega t) \tag{15}$$

$$\varepsilon_K = \frac{1}{2}\epsilon_0 k^2\Phi_0^2\left(1 + \sum_{s=u,d}\frac{\omega_{pes}^2}{\left(v_{Fes}^2 + \frac{1}{9}\frac{\hbar^2k^2}{4m_e^2}\right)k^2}\right) \times \sin^2(kx - \omega t) \tag{16}$$

$$\varepsilon_Q = \frac{1}{2}\epsilon_0 k^2\Phi_0^2\sum_{s=u,d}\frac{\omega_{pes}^2}{\left(v_{Fes}^2 + \frac{1}{9}\frac{\hbar^2k^2}{4m_e^2}\right)k^2} \times \cos^2(kx - \omega t) \tag{17}$$

$$\Gamma_{xE} = \Gamma_{xU} = 0 \tag{18}$$

$$\Gamma_{xQ} = \epsilon_0\Phi_0^2\left[\frac{\omega_{pi}\left(\frac{\omega_{peu}^2\left(v_{Fed}^2 + \frac{1}{9}\frac{\hbar^2k^2}{4m_e^2}\right)^{\frac{1}{2}}}{\left(v_{Feu}^2 + \frac{1}{9}\frac{\hbar^2k^2}{4m_e^2}\right)^{\frac{1}{2}}} + \frac{\omega_{ped}^2\left(v_{Feu}^2 + \frac{1}{9}\frac{\hbar^2k^2}{4m_e^2}\right)^{\frac{1}{2}}}{\left(v_{Fed}^2 + \frac{1}{9}\frac{\hbar^2k^2}{4m_e^2}\right)^{\frac{1}{2}}}\right)}{\left[\left(v_{Feu}^2 + \frac{1}{9}\frac{\hbar^2k^2}{4m_e^2}\right)\left(v_{Fed}^2 + \frac{1}{9}\frac{\hbar^2k^2}{4m_e^2}\right)k^2 + \omega_{peu}^2\left(v_{Fed}^2 + \frac{1}{9}\frac{\hbar^2k^2}{4m_e^2}\right) + \omega_{ped}^2\left(v_{Feu}^2 + \frac{1}{9}\frac{\hbar^2k^2}{4m_e^2}\right)\right]^{\frac{1}{2}}}\right] \times \cos^2(kx - \omega t). \tag{19}$$

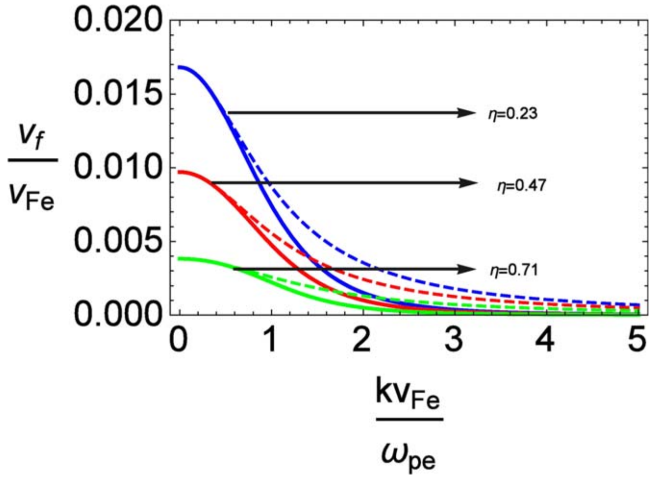

Figure 1. Figure represents the effect of spin polarization on the flow speed for ion acoustic wave. In this figure solid curves show the flow speed with Bohm potential effect whereas dashed ones represent the same without Bohm potential effect. The different values of η corresponding to magnetic field $B_0 = (1\text{–}3) \times 10^9 G$ and density $n_0 = 10^{24}\ \mathrm{cm}^{-3}$ are used for plotting.

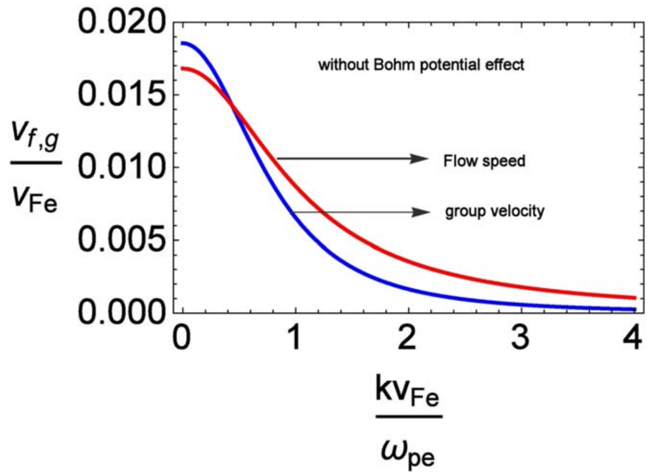

Figure 2. Figure shows the comparison of energy flow speed and group velocity for ion acoustic wave in spin polarized plasma without Bohm potential effect. Here we used parameter $B_0 = (1\text{–}3) \times 10^9 G$, density $n_0 = 10^{24}\ \mathrm{cm}^{-3}$ and $\eta = 0.23$.

Now we find the time-averaged values $\langle\varepsilon\rangle = \langle\varepsilon_E\rangle + \langle\varepsilon_K\rangle + \langle\varepsilon_Q\rangle$ and $\langle\Gamma_x\rangle = \langle\Gamma_E\rangle + \langle\Gamma_K\rangle + \langle\Gamma_Q\rangle$ of energy density and energy flux density, respectively, given by

$$\langle\varepsilon\rangle = \frac{1}{2}\epsilon_0 k^2 \Phi_0^2 \left(1 + \sum_{s=u,d} \frac{\omega_{pes}^2}{\left(v_{Fes}^2 + \frac{1}{9}\frac{\hbar^2 k^2}{4m_e^2}\right)k^2}\right), \tag{20}$$

$$\langle\Gamma_x\rangle = \frac{\epsilon_0 \Phi_0^2}{2} \times \left[\frac{\omega_{pi}\left(\frac{\omega_{peu}^2\left(v_{Fd}^2 + \frac{1}{9}\frac{\hbar^2k^2}{4m_e^2}\right)^{\frac{1}{2}}}{\left(v_{Fu}^2 + \frac{1}{9}\frac{\hbar^2k^2}{4m_e^2}\right)^{\frac{1}{2}}} + \frac{\omega_{ped}^2\left(v_{Fu}^2 + \frac{1}{9}\frac{\hbar^2k^2}{4m_e^2}\right)^{\frac{1}{2}}}{\left(v_{Fd}^2 + \frac{1}{9}\frac{\hbar^2k^2}{4m_e^2}\right)^{\frac{1}{2}}}\right)}{\left[\begin{array}{c}\left(v_{Fu}^2 + \frac{1}{9}\frac{\hbar^2k^2}{4m_e^2}\right)\left(v_{Fd}^2 + \frac{1}{9}\frac{\hbar^2k^2}{4m_e^2}\right)k^2 \\ +\omega_{pu}^2\left(v_{Fd}^2 + \frac{1}{9}\frac{\hbar^2k^2}{4m_e^2}\right) + \omega_{pd}^2\left(v_{Fu}^2 + \frac{1}{9}\frac{\hbar^2k^2}{4m_e^2}\right)\end{array}\right]^{\frac{1}{2}}}\right]. \tag{21}$$

Finally, we use $v_f = \frac{\langle\Gamma_x\rangle}{\langle\varepsilon\rangle}$ for the determination of energy flow speed for ion acoustic wave in spin polarized quantum plasma, which turns out to be

$$v_f = \frac{\omega_{pi}\omega_{peu}^2\left(v_{Fu}^2 + \frac{1}{9}\frac{\hbar^2k^2}{4m_e^2}\right)^{\frac{1}{2}}\left(v_{Fd}^2 + \frac{1}{9}\frac{\hbar^2k^2}{4m_e^2}\right)^{\frac{3}{2}} + \omega_{pi}\omega_{ped}^2\left(v_{Fd}^2 + \frac{1}{9}\frac{\hbar^2k^2}{4m_e^2}\right)^{\frac{1}{2}}\left(v_{Fu}^2 + \frac{1}{9}\frac{\hbar^2k^2}{4m_e^2}\right)^{\frac{3}{2}}}{\left[\left(v_{Fu}^2 + \frac{1}{9}\frac{\hbar^2k^2}{4m_e^2}\right)\left(v_{Fd}^2 + \frac{1}{9}\frac{\hbar^2k^2}{4m_e^2}\right)k^2 + \omega_{peu}^2\left(v_{Fd}^2 + \frac{1}{9}\frac{\hbar^2k^2}{4m_e^2}\right) + \omega_{ped}^2\left(v_{Fu}^2 + \frac{1}{9}\frac{\hbar^2k^2}{4m_e^2}\right)\right]^{\frac{3}{2}}}. \tag{22}$$

In the next section we analyze equations (11) and (22) numerically for the characterization of group velocity and energy flow speed.

3. Numerical results and discussion

The electron spin effects in plasma play an important role when the Zeeman energy attributed to the magnetic field is comparable or larger than the thermal energy i.e. $\mu_B B_0/k_B T \geqslant 1$. We choose the parameters from astrophysical environment i.e. density $n_0 = (10^{23}\text{–}10^{24})\ \mathrm{cm}^{-3}$ and magnetic field $B_0 = (10^8\text{–}10^9)G$ for which the Fermi temperature T_F of the system corresponding to this density is 4.23×10^5 K. Moreover, for the qualification of degenerate plasma the condition $T < T_F = 4.23 \times 10^5$ K must to be satisfied. The above mentioned conditions are only fulfilled when $T < 10^3$ K and $B_0 > 10^5 G$. Within these limits the spin effect plays significant role in the dispersion of waves. We have analyzed numerically the energy flow speed for an ion acoustic wave in comparison with the group velocity in a spin polarized quantum plasma including the Bohm potential effect. We have plotted the energy flow speed versus wave number in figure (1) for different values of spin polarization factor e.g. $\eta = 0.23$ (blue), 0.47 (red), 0.71 (green). It is clear from the figure (1) that the energy flow speed is supressed with the spin polarization factor. The acoustic wave is driven by the electron Fermi pressure which is modified due to spin polarization effect. Thus the main reason for the change in dispersion of ion acoustic wave as well as its energy flow speed is the difference in Fermi pressures of spin-up and spin-down electrons. The solid curves are drawn by taking the

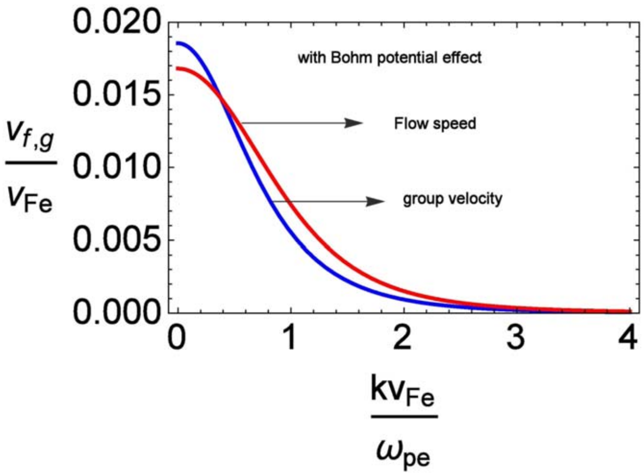

Figure 3. Figure shows the comparison of energy flow speed and group velocity for ion acoustic wave in spin polarized plasma with the Bohm potential effect. Here we used the parameter $B_0 = (1\text{–}3) \times 10^9 G$, density $n_0 = 10^{24}\,\text{cm}^{-3}$ and $\eta = 0.23$.

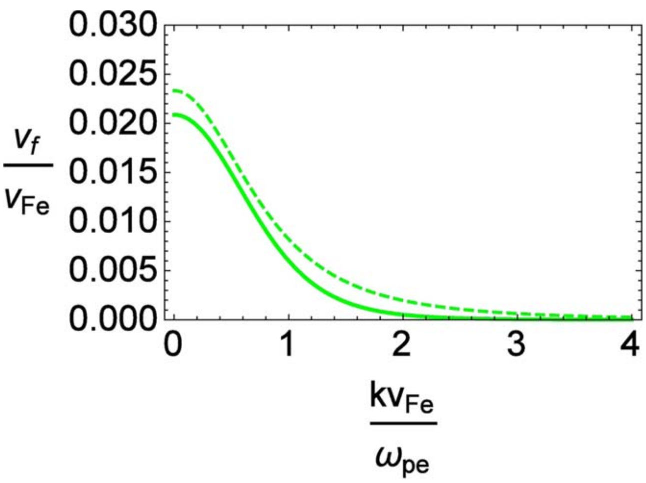

Figure 4. Figure shows the comparison of energy flow speed without (dashed green curve) and with (solid green curve) spin polarization effect. The parameter are same as used in figure 2.

Bohm potential effect in account whereas the dashed ones are traced without Bohm potential effect. It is evident from the figure that energy flow speed decreases with increasing rate initially with the wave number and then becomes zero asymtotically. The difference in the energy flow speed at different values of η is significantly large in long wavelength limit which then decreases gradually with the wave number. It is clear from the diagram that the Bohm potential is ineffective in the long wavelength limit but plays an important role in short wavelength range. In a spinless quantum plasma, it was reported that the energy flow speed and group velocity differ from each other in the presence of Bohm potential effect while in its absence both appear to be the same [44]. In our present study of spin polarized plasma, it is observed in figure (2) that the energy flow speed and group velocity are different even in the absence of Bohm potential. Figure (3) depicts that the deviation of energy flow speed from the group velocity reduces in the presence of Bohm potential effect.

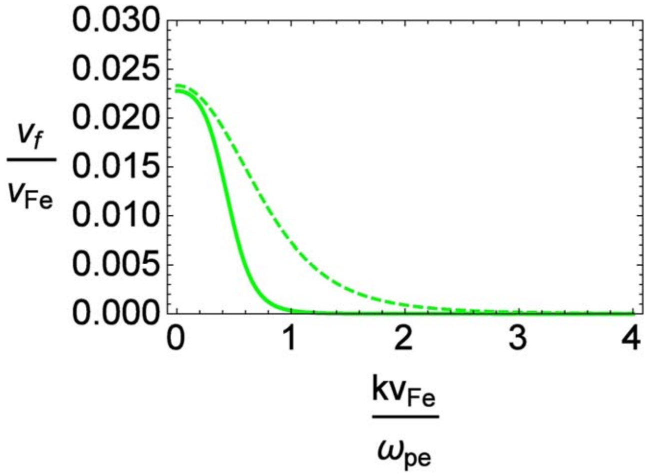

Figure 5. Figure shows the comparison of energy flow speed for the solid state parameters: $B_0 = 1 \times 10^6 G$, density $n_0 = 10^{20}\,\text{cm}^{-3}$ and $\eta = 0.11$. In this figure dashed green curve shows flow speed without spin polarization while the solid curve shows flow speed with spin polarization.

Further, it is also noticed that the energy flow speed is smaller than the group velocity in a small domain of long wavelength but this trend flips over around $k = 0.5$. The main result of our present work is that, in a spin polarized quantum plasma, the energy transport is no longer governed by the group velocity. The spin polarization parameter η appears when the electrons are treated as two different fluids and is defined as $\eta = (n_{0u} - n_{0d})/n_0 = 3\mu_B B_0/2\varepsilon_{Fe}$. By changing spin polarization factor via magnetic field means actully we change the concentration of spin-up and spin-down particles. Thus if we treat the electrons as single fluid then there is no spin effect on the dispersion of ion acoustic wave as well as the energy flow speed. Further, the energy flow speed for ion acoustic wave without spin effect [44] is given as

$$v_f = \frac{\omega_{pi}\omega_{pe}^2\left(v_{Fe}^2 + \frac{1}{9}\frac{\hbar^2 k^2}{4m_e^2}\right)^{\frac{1}{2}}}{\left[\omega_{pe}^2 + \left(v_{Fe}^2 + \frac{1}{9}\frac{\hbar^2 k^2}{4m_e^2}\right)k^2\right]^{\frac{3}{2}}}.$$

We have compared the energy flow speed for ion acoustic wave with and without spin polarization effect in figure (4). It is clear from the figure that spin polarization effect reduces the energy flow speed. We have also plotted the flow speed as shown in figure (5) for low values of density and magnetic field, for instance, $n_0 = 10^{20}\,\text{cm}^{-3}$ and $B_0 = 10^6 G$ which are typically found in the semiconductor plasma. We took the electron effective mass, replaced ions with holes and e^2 in the expression of ω_{pe} is replaced by e^2/ϵ_0 (where ϵ_0 is the lattice dielectric constant of the crystal) to obtain the results for solid state plasma. We conclude that, energy flow speed of ion acoustic wave is driven by the pressure which is now modified by spin polarization effect. It is clear that the flow speed is supperessed for both the high and low values of density and magnetic field in a spin polarized plasma.

4. Summary and conclusion

In the present work, we have investigated the energy flow speed for an ion acoustic wave in a spin quantum plasma. We have used SSE-QHD model for taking the spin dynamics of electrons into account. It is observed that energy flow speed reduces when spin polarization parameter η increases. The change in speed due to η is appreciably large in short wavelength limit. Further, the speed falls rapidly with k in the presence of Bohm potential effect in comparison with the case when it is absent. Finally, the energy flow speed and the group velocity are shown to be different in both the situations. Thus, we conclude that in SSE-QHD model the energy transport is governed by energy flow speed rather than the group velocity.

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