Group velocity of extraordinary waves in superdense magnetized quantum plasma with spin-1/2 effects

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Based on the one component plasma model, a new dispersion relation and group velocity of elliptically polarized extraordinary electromagnetic waves in a superdense quantum magnetoplasma are derived. The group velocity of the extraordinary wave is modified due to the quantum forces and magnetization effects within a certain range of wave numbers. It means that the quantum spin-1/2 effects can reduce the transport of energy in such quantum plasma systems. Our work should be of relevance for the dense astrophysical environments and the condensed matter physics. [http://dx.doi.org/10.1063/1.4773046]

I. INTRODUCTION

Quantum plasmas have attracted much attention due to its wide applications in different areas, such as in astrophysical objects,[1] nanoscale electromechanical systems,[2] ultracold plasmas[3] as well as in intense laser-solid density plasma interaction experiments.[4–7] Moreover, it has recently been experimentally shown that quantum effects are important in inertial confinement fusion (ICF) plasmas.[8] In quantum plasmas, when the de Broglie wavelength of the charged carriers becomes comparable to the dimensions of the system (such as interparticle distances), quantum effects start playing a role. In the quantum regime, the plasma obeys certain conditions, as discussed by Manfredi.[9] It should be mentioned that the equilibrium distribution function of the degenerate electrons follows the Fermi-Dirac statistics in dense quantum plasmas, and there are new aspects of collective interactions due to the forces involving electron tunneling through the quantum Bohm potential and electron spin effects.[10] There are three well-known models to describe quantum plasma systems, the Wigner-Poisson (WP) model (in the presence of magnetic fields, the so-called Wigner-Maxwell model), Hartree model, and quantum hydrodynamic (QHD) model. The WP model describes the statistical behavior of quantum plasmas, whereas the Hartree model describes the hydrodynamic behavior.[9] The QHD model, which represents the transport of some microscopic variables such as, charge, momentum, and energy in plasmas has been introduced to deal with some issues in semiconductor physics.[11] As a fluid model, the QHD model has the advantage of mathematical efficiency and can be derived from the WP model and/or the Hartree model.[9,12,13] It has been extensively used in the study of quantum plasmas transport, waves, and instabilities. The quantum magnetohydrodynamic (QMHD) model has also been obtained using the QHD model with magnetic fields based on the Wigner-Maxwell equations.[13]

The concept of spin magnetohydrodynamics has attracted much interest since it was introduced by Brodin and Marklund.[14] Since then, quantum effects including the Bohm potential and electron spin-1/2 effects have been studied by many researchers. As described in Ref. 15, Marklund and Brodin investigated the linear response of the quantum plasma in an electron-ion system and derived the relevant plasma equations. Very recently, some researchers[16] studied the oblique propagation of low-frequency magnetosonic waves in spin-1/2 degenerate magnetoplasma composed by mobile ions, electrons, and positrons. They found that the effect of quantum corrections in the presence of positron concentration significantly modified the dispersive properties. The magnetoacoustic solitons in a quantum magnetoplasma with Bohm potential and electron spin-1/2 effects were studied by Marklund, Eliasson, and Shukla,[17] and it was shown that the electron spin-1/2 effects modified the shape of the solitary magnetoacoustic waves. Saleem *et al.*[18] studied the quantum corrections in the linear dispersion relations of cold dense plasmas, and the low frequency electrostatic and electromagnetic linear modes in nonuniform cold quantum electron-ion plasma were presented. Nonlinear magnetosonic waves in degenerate plasmas were discussed using the spin-1/2 QMHD model in Ref. 19, and the authors studied both limited and arbitrary amplitude magnetosonic soliton. Ren, Wu, and Chu[20] derived the dispersion of linear waves in uniform cold quantum plasma without the spin-1/2 effects. Using the QHD and Maxwell's equations, nonlinear electromagnetic wave (EMW) equations for superdense magnetized plasmas were derived by Shukla *et al.*[21] A generalized set of nonlinear electromagnetic quantum hydrodynamic equations is derived for magnetized quantum plasma, including collision, electron spin-1/2, and relativistically degenerate electron pressure effects,[22] and the results are relevant to dense astrophysical systems. The effects of strong fields on single particles with spin effect have attracted experimental interest in the laser field,[23] where the treatment of these studies is based on single particle dynamics. The nonlinear collective processes in quantum plasmas

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with degenerate electrons were presented in details by Shukla and Eliasson.[10] Using a classical relativistic model, the properties of waves in a cold magnetized electron gas including the effect of spin dependence were proposed by Ref. 24. Oraevsky and Semikoz[25] have examined the spin waves in dense magnetized plasma and found the growth rate of the electromagnetic spin waves in the presence of intense quasi-monoenergetic fluxes of neutrinos. The influence of the electron spin-1/2 effect on the propagation of circularly polarized waves in magnetized plasma has been analyzed by Misra *et al.*,[26] and new eigenmodes are identified.

In this present work, we analyze the quantum corrections to the elliptically polarized extraordinary electromagnetic waves while ignoring quantum electrodynamical (QED) and relativistic effects. Here, the model is based on the one component plasma which is one of the basic models in the condensed matter physics.[27,28] This model can be used when quantum effects are important.[29] Besides of its direct astrophysical applications,[28] to model the ionized matter in white dwarfs,[30] outer layers of neutron stars and interiors of heavy planets.[31,32] The quantum effect due to the quantum tunnelling is described by Bohm potential and quantum spin-1/2 effects are characterized by the spin quantum force as well as spin magnetization current. When spin-1/2 effects are included, the intrinsic magnetic moment of the plasma constituents gives rise to several new effects, principally due to the magnetic dipole force and spin magnetization current. The quantum effects can produce some new aspects of EMWs in quantum plasmas. Meanwhile, we show that the spin-1/2 effects reduce the group velocity in superdense quantum plasmas. A wave-packet is a bundle of energy and the group velocity is the velocity of the traveling bundle. That is to say, the group velocity represents the speed of energy transport. It is thus meaningful to study the group velocity in superdense quantum plasmas in certain astronomical circumstance.

This paper is organized in the following fashion: In Sec. II, we use the quantum magnetohydrodynamic model to calculate the dispersion relation of elliptically polarized extraordinary electromagnetic waves in uniform quantum plasmas with nonzero external magnetic field. Section III is devoted to analysis and discussions on the group velocity of the extraordinary electromagnetic waves, and the cutoffs and resonances are also analyzed in this section. The conclusion is given in Sec. IV.

II. ASSUMPTIONS AND EQUATIONS

We suppose that the superdense quantum plasma is composed of electrons and ions. The ions are assumed to be stationary since their inertia is too large for them to response to a high-frequency wave and its quantum effects can be ignored because of the same reason. Meanwhile, the plasma is assumed to be embedded in an external magnetic field $\mathbf{B_0} = B_0\hat{e}_z$, where $\hat{e}_z$ is the unit vector along the Z-axis in a Cartesian coordinate system and B_0 is the strength of the background magnetic field.

The basic equations of electromagnetic waves for QMHD including the electron spin-1/2 effects are composed of the equation of motion,

$$m_e n_e \frac{d\mathbf{u}}{dt} = -en_e(\mathbf{E} + \mathbf{u}\times\mathbf{B}) - \nabla P + n_e\mathbf{F_Q}. \tag{1}$$

The Faraday's law,

$$\nabla\times\mathbf{E} = -\frac{\partial\mathbf{B}}{\partial t} \tag{2}$$

and Maxwell's equation including the electron magnetization spin current,

$$\nabla\times\mathbf{B} = \mu_0\left(\mathbf{J} + \varepsilon_0\frac{\partial\mathbf{E}}{\partial t} + \mathbf{J}_m\right). \tag{3}$$

Here, we use SI units. $d/dt = \partial/\partial t + (\mathbf{u}\cdot\nabla)$ is the hydrodynamic derivative, m_e is electron mass, n_e is electron number density, n_0 is the equilibrium number density of electrons, e is the magnitude of the electronic charge, $\mathbf{u}$ is the electron fluid velocity, $\mathbf{E}$ and $\mathbf{B}$ are the electric and magnetic field vectors, μ_0 is the magnetic permeability, ε_0 is the vacuum electric conductivity. $\mathbf{J} = -en_0\mathbf{u}$ is the current density due to free electrons and the electron magnetization spin current density is given by

$$\mathbf{J}_m = \nabla\times\mathbf{M}. \tag{4}$$

Here, the term $\mathbf{M} = n_e\mu_B^2\mathbf{B}/k_BT_{Fe}$ is the macroscopic spin magnetization in a completely degenerate Fermi gas (so-called Pauli spin magnetization).[19,33] Where, $\mu_B = e\hbar/2m_e$ is the Bohr magneton and k_B is the Boltzmann constant. $\hbar$ is Planck's constant divided by 2π. T_{Fe} is the electron Fermi temperature defined as $T_{Fe} \equiv E_{Fe}/k_B = (\hbar^2/2m_ek_B)(3\pi^2)^{2/3}n_e^{2/3}$, where E_{Fe} is the Fermi energy.

In the following equations, every quantity φ (representing $\mathbf{u}$, $\mathbf{E}$, $\mathbf{B}$, $\mathbf{M}$, etc.) has the following form:

$$\varphi = \varphi_0 + \varphi_1, \tag{5}$$

where φ_0 is the unperturbed value and $\varphi_1(\ll\varphi_0)$ is a small perturbation

$$\varphi_1 \propto \exp(-i\omega t + i\mathbf{k}\cdot\mathbf{r}). \tag{6}$$

It should be pointed out that the quantum fermionic pressure in the first equation can be written as[9,34]

$$P = 2T_{Fe}n_1, \tag{7}$$

and $n_1(\ll n_0)$ is a small electron density perturbation.

The first order quantum force F_Q on an electron with spin-1/2 effects is[16]

$$\mathbf{F}_Q = \frac{\hbar^2}{4m_en_0}\nabla\nabla^2 n_1 + \frac{2\mu_B}{\hbar}\nabla(\mathbf{s}\cdot\mathbf{B_1}), \tag{8}$$

where the first term in the right hand side of Eq. (8) is associated with the quantum Bohm potential gradient (corresponding to the quantum corrections in the density fluctuations) and the second is the spin magnetization force due to the electron-1/2 spin effects, respectively. The spin evolution equation for spin quantum plasmas is given by[15,19]

$$\frac{d\mathbf{s}}{dt} = \frac{2\mu_B}{\hbar}(\mathbf{s}\times\mathbf{B}). \tag{9}$$

The spin-thermal coupling terms in Eq. (9) have been neglected. Equation (9) is similar to the classical precession equation for the spin with the spin correction to the magnetic field.[36] In MHD, one knows that the scale lengths are typically longer than the Larmor radius of the electrons, so the terms that are quadratic in **s** can be ignored in the spin evolution equation (9). To lowest order, the spin inertia can be neglected for frequencies much below the electron cyclotron frequencies, which gives the spin equation (9) as $\mathbf{s}\times\mathbf{B}=0$, and has a solution[14,16]

$$\mathbf{s}=-\frac{\hbar}{2}\eta\left(\frac{\mu_B B_0}{k_B T_{Fe}}\right)\hat{\mathbf{B}}. \quad (10)$$

The Langevin parameter $\eta(\alpha)=\tanh(\alpha)$ is due to the magnetization of a spin distribution in thermodynamic equilibrium.[16] Where, $\alpha=\mu_B B_0/k_B T_{Fe}$ and T_{Fe} is the Fermi temperature of degenerate electrons. As for Maxwellian plasma, the Fermi temperature T_{Fe} will be replaced by the Maxwellian temperature T_e.

Plasma equilibrium is assumed, $\mathbf{E}_0=0, \mathbf{u}_0=0$. The perturbed electric field $\mathbf{E}_1$ and electron fluid velocity $\mathbf{u}_1$ are in the X-O-Y plane. The wave vector **k** is along the X-axis. The basic geometry of the model is described in Fig. 1.

Now, we are considering the propagation of elliptically polarized extraordinary electromagnetic waves in superdense quantum plasmas, and the basic linearized equations in such quantum plasmas system can be obtained in the following:

$$\nabla\times\mathbf{E}_1=-\frac{\partial\mathbf{B}_1}{\partial t}, \quad (11)$$

$$\nabla\times\mathbf{B}_1=\mu_0\left(\mathbf{J}_1+\varepsilon_0\frac{\partial\mathbf{E}_1}{\partial t}+\nabla\times\mathbf{M}_1\right), \quad (12)$$

$$m_e n_0\frac{\partial\mathbf{u}_1}{\partial t}=-en_0(\mathbf{E}_1+\mathbf{u}_1\times\mathbf{B}_0)-\nabla P+n_0\mathbf{F}_Q. \quad (13)$$

The perturbed electron magnetization density and electron number density perturbation are given by

$$\mathbf{M}_1=\frac{n_0\mu_B^2}{k_B T_{Fe}}\mathbf{B}_1+\frac{n_1\mu_B^2}{k_B T_{Fe}}\mathbf{B}_0, \quad (14)$$

$$\nabla\cdot\mathbf{E}_1=-\frac{e}{\varepsilon_0}n_1. \quad (15)$$

We focus on the extraordinary electromagnetic wave propagation along the x-axis. From Eqs. (12) to (15), we obtain

$$\nabla\times(\nabla\times\mathbf{E}_1)=\frac{1}{\chi}\left\{en_0\mu_0\frac{\partial\mathbf{u}_1}{\partial t}-\frac{1}{c^2}\frac{\partial^2\mathbf{E}_1}{\partial t^2}+\frac{\mu_B^2}{c^2 eE_{Fe}}\frac{\partial}{\partial t}[(\nabla(\nabla\cdot\mathbf{E}_1))\times\mathbf{B}_0]\right\}, \quad (16)$$

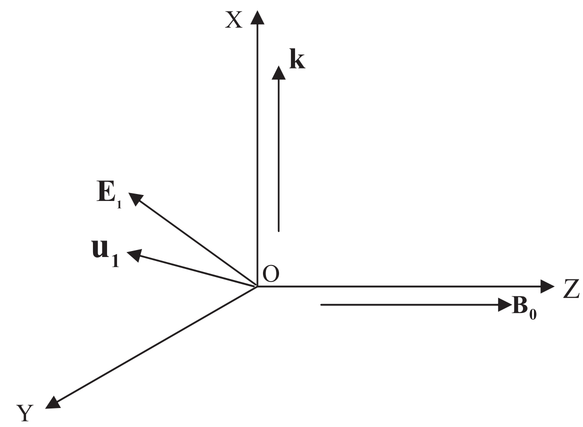

FIG. 1. Geometry of extraordinary electromagnetic waves propagating perpendicular to $\mathbf{B_0}$.

where c is the speed of light in vacuum and

$$\chi\equiv 1-\frac{n_0\mu_0\mu_B^2}{k_B T_{Fe}}. \quad (17)$$

Taking into account the X- and Y-components of electric field $\mathbf{E}_1$, using Fourier transform, we then yield

$$-i\omega E_x=\frac{en_0}{\varepsilon_0}u_x \quad (18)$$

and

$$(k^2c^2-\omega^2)E_y=-\frac{i\omega en_0}{\chi\varepsilon_0}u_y. \quad (19)$$

Also, from Eqs. (12) to (15), we derive

$$\frac{\partial\mathbf{u}_1}{\partial t}=-\frac{e}{m_e}(\mathbf{E}_1+\mathbf{u}_1\times\mathbf{B}_0)+\frac{\varepsilon_0}{en_0}v_F^2\nabla(\nabla\cdot\mathbf{E}_1)-\frac{\varepsilon_0\hbar^2}{4m_e^2 en_0}\nabla^2[\nabla(\nabla\cdot\mathbf{E}_1)]-\frac{1}{m_e}\eta(\alpha)\mu_B\nabla B_z, \quad (20)$$

where $v_F^2=2T_{Fe}/m_e$ is the Fermi velocity. After performing Fourier transform and taking into account the X- and Y-components of electron fluid velocity $\mathbf{u}_1$, the following relationship is obtained:

$$-i\omega u_x=-\frac{e}{m_e}\left(1+\frac{\lambda_F^2k^2}{\omega_{pe}^2}+\frac{\hbar^2k^4}{4m_e^2\omega_{pe}^2}\right)E_x-u_y\omega_{ce}-ik\eta(\alpha)\frac{e\hbar}{2m_e^2}\frac{k}{\omega}E_y, \quad (21)$$

$$-i\omega u_y=-\frac{e}{m_e}E_y+u_x\omega_{ce}. \quad (22)$$

From Eqs. (18), (19), (21), and (22), the following dispersion relation of the quantum plasmas is derived

$$Det\begin{vmatrix}\omega_{pe}^2-\omega^2+v_F^2k^2+\frac{\hbar^2k^4}{4m_e^2} & i\left[\frac{\chi\omega_{ce}}{\omega}(k^2c^2-\omega^2)+\eta(\alpha)k^2\omega_{pe}^2\lambda_B^2\right]\\ i\omega_{ce}\omega & \omega_{pe}^2-\chi(\omega^2-k^2c^2)\end{vmatrix}=0, \quad (23)$$

where, ω_{pe} and ω_{ce} are the electron plasma and the electron gyro-frequencies, respectively, and $\lambda_B^2 = \hbar/2m_e\omega_{ce}$ is an auxiliary quantity.

It is noted that there is a factor χ in the Eq. (23). In the absence of spin magnetization current, $\chi = 1$. But, in the presence of spin-1/2 effects and at very high electron number densities, the sign of χ can, in principle, be changed from Eq. (17). Next, we consider two cases of Eq. (23).

A. χ=1

There is no electron magnetization spin current in this case and the dispersion relation of Eq. (23) can be expressed in the form of refractive index which is similar to that reported in Ref. 34.

$$n^2 = \frac{k^2c^2}{\omega^2} = 1 - \frac{\omega_{pe}^2}{\omega^2} - \frac{\omega_{pe}^2\omega_{ce}^2[1-\eta(\alpha)k^2\lambda_B^2]}{\omega^2[\omega^2 - \omega_H^2 - k^2v_F^2(1+k^2\lambda_q^2)]}. \quad (24)$$

Here, $\lambda_q = \hbar/2m_eV_F$ is the quantum type wavelength of electron and $\omega_H = \sqrt{\omega_{pe}^2 + \omega_{ce}^2}$ is the upper-hybrid (UH) resonance frequency.

B. $\chi \neq 1$

In order to verify all of the quantum effects including electron magnetization spin current, we derive a new dispersion relation in the following form, from which we can obtain the quantum corrections to the dispersion relation

$$n^2 = \frac{k^2c^2}{\omega^2} = 1 - \frac{\omega_{pe}^2}{\chi\omega^2} - \frac{\omega_{pe}^2\omega_{ce}^2[1-\eta(\alpha)k^2\lambda_B^2]}{\chi\omega^2[\omega^2 - \omega_H^2 - k^2v_F^2(1+k^2\lambda_q^2)]}. \quad (25)$$

There are two different terms which contain the factor χ in Eq. (25). It is found that the χ term is due to the influence of the electron magnetization spin current in the quantum plasmas. One can retrieve the former relation of Eq. (24) when ignoring electron magnetization spin current.

III. ANALYSIS AND DISCUSSIONS

In Sec. II, the dispersion relationship of elliptically polarized extraordinary electromagnetic waves is derived and in this section, we examine the influence of quantum effects on the group velocity. Meanwhile, we discuss the cutoffs and resonances of extraordinary electromagnetic waves in such quantum plasmas system.

Ignoring electron magnetization spin current, we have obtained the dispersion relationship of Eq. (24) which takes into account the Bohm potential as well as spin quantum force. It is noted that the quantum Bohm potential and spin quantum force modify the dispersion relation appreciably. The Bohm potential leads to a dispersion term $\hbar^2k^4/4m_e^2$ in the denominator of the third term in Eq. (24) and the electron spin-1/2 effect reduces the gyrofrequency by a factor $(1-\eta(\alpha)k^2\lambda_B^2)$ in the numerator of the third term on the right hand side of Eq. (24). If we ignore all the $\hbar-$dependent terms which stand for the quantum effects, we then obtain classical extraordinary electromagnetic wave dispersion relation in Ref. 35.

A. Group velocity of extraordinary waves

We now consider the extraordinary wave group velocity from the new dispersion relation and obtain the group velocity relations in the following:

$$\frac{d\omega_1}{dk} = v_{g1} = \frac{AD - AB + 2\chi C}{D\sqrt{2\chi(\mathrm{B}-D)}} \quad (26)$$

and

$$\frac{d\omega_2}{dk} = v_{g2} = \frac{AD + AB - 2\chi C}{D\sqrt{2\chi(\mathrm{B}+D)}}. \quad (27)$$

In Eqs. (26) and (27), the corresponding capital letters are given by

$$A = k\chi(c^2 + v_F^2) + 2k^3\chi v_F^2\lambda_q^2, \quad (28a)$$

$$B = k^2\chi(c^2+v_F^2) + \chi(\omega_H^2 + k^4v_F^2\lambda_q^2) + \omega_{pe}^2, \quad (28b)$$

$$C = c^2k\chi(2k^2v_F^2 + \omega_H^2) + k\omega_{pe}^2(v_F^2 + \eta(\alpha)\omega_{ce}^2\lambda_B^2) + k^3v_F^2\lambda_q^2(3c^2k^2\chi + 2\omega_{pe}^2), \quad (28c)$$

$$D = \sqrt{B^2 - 4\chi E}, \quad (28d)$$

$$E = c^2k^2\chi(k^2v_F^2 + \omega_H^2) + \omega_{pe}^2(k^2v_F^2 + \omega_{pe}^2) + k^2\eta(\alpha)\omega_{ce}^2\omega_{pe}^2\lambda_B^2 + k^4v_F^2\lambda_q^2(c^2k^2\chi + \omega_{pe}^2). \quad (28e)$$

Here, v_{g1} and v_{g2} are two branches of the group velocity of extraordinary waves, respectively.

B. Cutoffs and resonances

The cutoffs of the extraordinary wave are found when n^2 is equal to zero in Eq. (25). We can write the resulting equation for ω as follows:

$$\frac{\omega_{pe}^2}{\chi\omega^2} + \frac{\omega_{pe}^2\omega_{ce}^2[1-\eta(\alpha)k^2\lambda_B^2]}{\chi\omega^2[\omega^2 - \omega_H^2 - k^2v_F^2(1+k^2\lambda_q^2)]} = 1. \quad (29)$$

When the quantum effects are all ignored and Eq. (29) will be simplified as the well-known classical cases[35]

$$\omega^2 \mp \omega\omega_{ce} - \omega_{pe}^2 = 0. \quad (30)$$

Each of the two signs will give a different cutoff frequency, we often call these ω_R and ω_L. The roots of the two quadratics are

$$\omega_L = \frac{1}{2}[-\omega_{ce} + (\omega_{ce}^2 + 4\omega_{pe}^2)^{1/2}], \quad (31a)$$

$$\omega_R = \frac{1}{2}[\omega_{ce} + (\omega_{ce}^2 + 4\omega_{pe}^2)^{1/2}]. \quad (31b)$$

Here, including all the quantum effects, and after a few tricky algebraic steps, one yields the simple expressions as following:

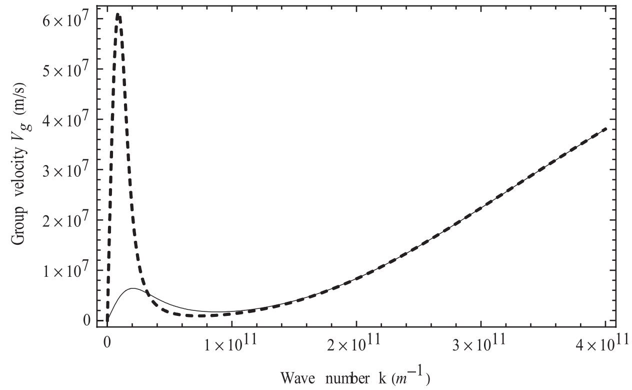

FIG. 2. Group velocity of one of the branches of extraordinary waves. The dashed line is for the Bohm potential effect only, and the continuous line is considering both the Bohm potential effect and the spin effect. The range of wave number k is between $8 \times 10^1 \mathrm{m}^{-1}$ and $4 \times 10^{11} \mathrm{m}^{-1}$.

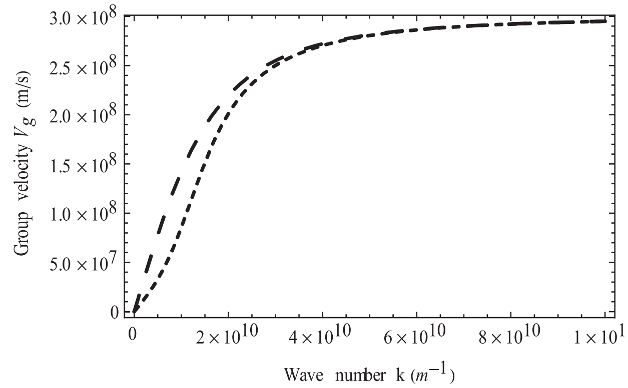

FIG. 4. Comparison between the Bohm potential correction and classical group velocity. The dashed line stands for the Bohm potential effect and the large-dashed line is for classical group velocity. The range of wave number k is between $8 \times 10^1 \mathrm{m}^{-1}$ and $1 \times 10^{11} \mathrm{m}^{-1}$.

$$\omega_{L,Q} = \frac{1}{2}\left[\frac{2(B-D)}{\chi}\right]^{1/2}, \tag{32a}$$

$$\omega_{R,Q} = \frac{1}{2}\left[\frac{2(B+D)}{\chi}\right]^{1/2}, \tag{32b}$$

where, the corresponding capital letters are given in Eqs. (28b), (28d), and (28e), the cutoff frequencies $\omega_{L,Q}$ and $\omega_{R,Q}$ are called the quantum left-hand and right-hand cutoffs, respectively.

The resonance of the extraordinary wave is found when n^2 is infinity in Eq. (25). And then, one can obtain the resulting resonance frequency from Eq. (25)

$$\omega^2 = \omega_H^2 + k^2 v_F^2 (1 + k^2 \lambda_q^2). \tag{33}$$

From the above discussions, we can see that the quantum effects can modify the characteristics of extraordinary wave's cutoffs and resonance.

Next, in order to show the influence of the group velocity on the quantum effects due to Bohm potential and electron spin-1/2 effects, we evaluate Eqs. (26) and (27) by substituting some typical parameters in the dense astrophysical objects (like the outer shells of magnetized white dwarf stars),[1,37] where the plasma density is $n_0 = 10^{34} \mathrm{m}^{-3}$, the temperature is about 10^5K and $B_0 \simeq 10^7$T.

Figure 2 shows one of the branches of extraordinary waves. The Bohm potential effect without spin-1/2 effects is indicated by dashed curve. The continuous curve stands for the Bohm potential effect as well as spin-1/2 effects which are represented by the spin quantum force and electron magnetization spin current. Compared to the dashed curve, the continuous curve is much wider and lower when the wave number is relatively small. With regard to the group velocity, the later one is also reduced in the same range of wave numbers.

Figure 3 represents the comparison chart of the other branch of extraordinary waves and the Bohm potential effect is characterized by the dashed curve. The continuous line stands for Bohm potential effect and spin-1/2 effect. As shown, the group velocity is somewhat reduced in a certain range of wave number when spin-1/2 effect is taken into account.

In the following, Figures 4 and 5 describe the comparison of quantum correction to the classical group velocity which is represented by the large-dashed line. The effect of quantum correction on the group velocity of extraordinary electromagnetic waves is apparent. The Bohm potential

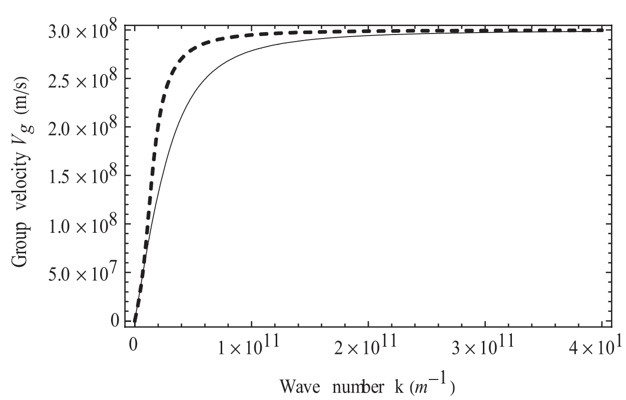

FIG. 3. Group velocity of the other branches of extraordinary waves. The dashed line is for the Bohm potential effect only, and the continuous line is considering both the Bohm potential effect and the spin–1/2 effect. The range of wave number k is between $8 \times 10^1 \mathrm{m}^{-1}$ and $4 \times 10^{11} \mathrm{m}^{-1}$.

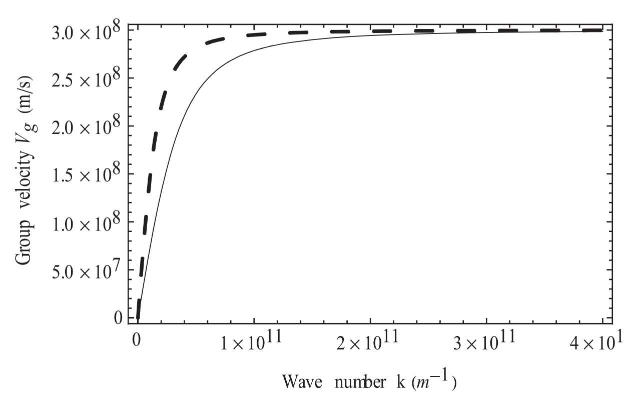

FIG. 5. Comparison between all the quantum corrections and classical group velocity. The continuous line stands for all the quantum corrections and the large-dashed line is for classical group velocity. The range of wave number k is between $8 \times 10^1 \mathrm{m}^{-1}$ and $1 \times 10^{11} \mathrm{m}^{-1}$.

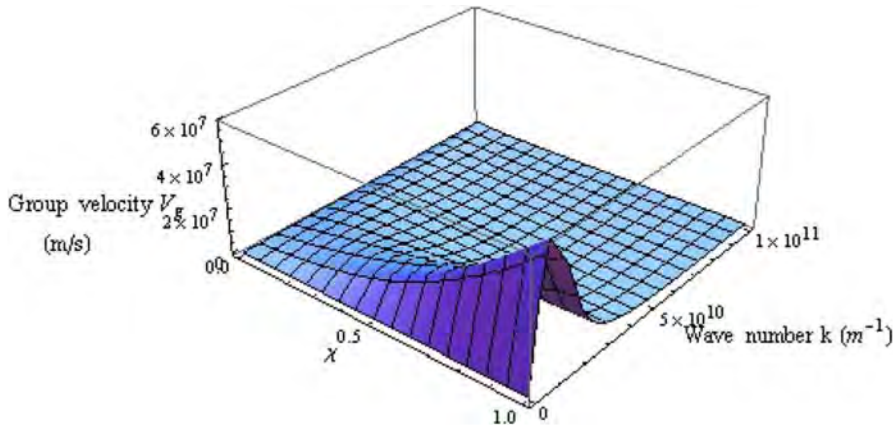

FIG. 6. Surface plot of one of the branches of the group velocity of extraordinary electromagnetic wave.The range of χ is between 0 and 1. The range of wave number k is between $8 \times 10^1 \mathrm{m}^{-1}$ and $1 \times 10^{11} \mathrm{m}^{-1}$.

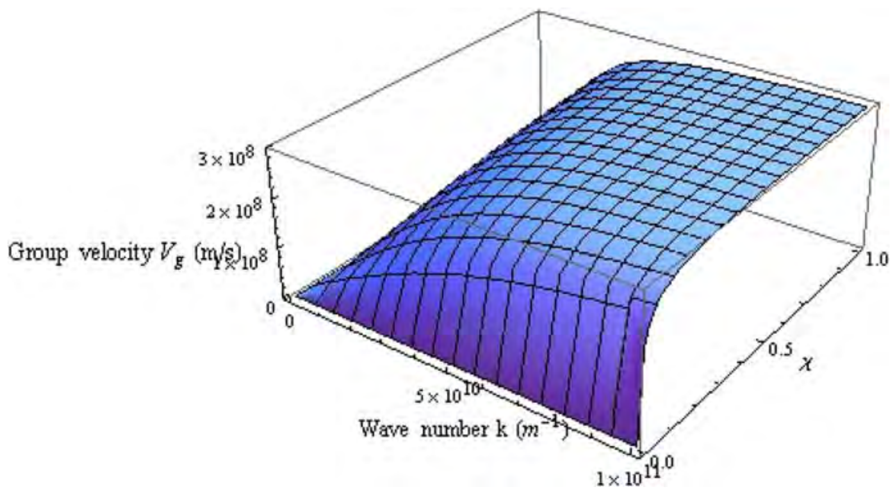

FIG. 7. Surface plot of the other branches of the group velocity of extraordinary electromagnetic wave in different ranges of χ and wave vector k. The range of χ is between 0 and 1. The range of wave vector k is between $8 \times 10^1 \mathrm{m}^{-1}$ and $1 \times 10^{11} \mathrm{m}^{-1}$.

effects or spin-1/2 effect can decrease the group velocity of the extraordinary electromagnetic waves. Similar to Figure 4, Figure 5 reveals that for the same range of wave number k, the group velocity of extraordinary electromagnetic waves becomes much smaller than that in the cases in which the Bohm potential effect is only considered. The influence of the Bohm potential effect and electron spin-1/2 effect on the group velocity of extraordinary waves in quantum plasmas is also shown in Figures 4 and 5. In order to explain the influence of the spin quantum force on the dynamics of our system, we give the corresponding explanation. The spin introduces an additional negative pressure-like term in the quantum momentum equation, and the effect is that the energy of extraordinary electromagnetic waves may be depleted for larger values of $\alpha = \mu_B B_0 / k_B T_{Fe}$. We also note that the spin term represented by $\eta(\alpha)$ and χ in Eq. (24) can dominate the sign of the dispersion relation.

In order to see the influence of different range of the factor χ, we then choose some parameters to make the value of this factor between 0 and 1, and plot the 3D image later in Figures 6 and 7. The group velocity of the extraordinary electromagnetic wave is changed significantly for different amplitudes of χ and wave number k, especially when the value of χ changes from 0 to 1, the group velocity of the extraordinary electromagnetic wave becomes bigger and bigger for a fixed wave number (like $\mathrm{k} = 1 \times 10^{10} \mathrm{m}^{-1}$).

With the purpose of studying the influence of the factor χ to the other branches of the group velocity, we also choose the same parameters and plot its 3D image in Fig. 7. We find that the existence of the electron spin-1/2 effects can change the profile of the group velocity. It is known that a wave-packet is a bundle of energy and the group velocity is the velocity of the traveling bundle. That is to say, the group velocity is the speed of the transport of energy. From the above discussions, we can conclude that the spin-1/2 effects can change the profile of the group velocity of extraordinary electromagnetic wave for a certain range of χ, and therefore the speed of the transport of energy is also changed in such quantum plasmas system.

IV. CONCLUSION

The elliptically polarized extraordinary electromagnetic waves propagation in superdense magnetized quantum plasmas with electron spin-1/2 effect is investigated. The modified dispersion relation and group velocity of extraordinary electromagnetic waves in spin-1/2 quantum plasmas are obtained. Our results show that existence of quantum effects can reduce the group velocity of electromagnetic waves in a superdense quantum magnetoplasma and the quantum corrections have significant effects on the dispersion properties of extraordinary electromagnetic waves. We roughly investigated the cutoffs and resonances of extraordinary electromagnetic waves in such quantum plasmas system, and found the cutoffs and resonances are modified due to the quantum corrections. We also found that the quantum spin-1/2 effects can reduce the energy transport in such quantum plasmas system. To summarize, the modified dispersion relations for high-frequency extraordinary electromagnetic waves in a superdense quantum magnetoplasma are obtained by taking into account the quantum forces (including electron tunneling effects and electron spin-1/2 effects). The electron magnetization spin current was also included in the Maxwell's equations. The study of quantum correction relations may be useful at least from the diagnostic points of view, since the observation of the propagation characteristics of the waves might be used in order to determine the physical parameters in plasmas.[26] Our results and conclusion are important for the understanding of the propagation characteristics of high-frequency elliptically polarized electromagnetic waves in superdense magnetoplasmas such as those in the dense astrophysical plasmas (the atmospheres of neutron stars, magnetars, and the interior and outer shell of massive white dwarfs)[38–40] in which electron spin effects can play an important role.

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