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The impact of quantized magnetic pressure on the stimulated Brillouin scattering of electromagnetic waves

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Abstract

Within the frame work of Landau quantization theory of Fermi gas, we formulate here the exotic physics of magnetic stimulated Brillouin scattering instability (MSBS) arising due to the nonlinear interaction of high frequency electromagnetic waves (EMWs) with degenerate, strongly magnetized electron-ion plasma. Quantum magneto hydrodynamic model (QMHD) is followed to develop the basic differential equations of quantized magnetosonic waves (QMWs) in the presence of super strong magnetic (SSH) field, whereas Maxwell equations are used to derive the governing differential equation of pump EMWs. The nonlinear interaction of EMWs and QMWs is addressed by employing the phasor matching technique. The obtained dispersion relation of MSBS shows that for a fixed density of fermions, the SSH field alone suppresses the MSBS instability as a function of quantized magneto ion velocity (C_{He}) and the Alfven speed (V_A) via three-wave decay and modulational instabilities. However, for particular condition the MSBS instability is found to increase as a function of SSH field. Next, the analytical results are verified numerically and graphically for soft x-rays in the environment of neutron star. The present MSBS analysis may be critical in neutron stars, radio pulsars and magnetars having super strong magnetic field i.e. even larger than the quantum threshold value i.e, $H \sim 4.4 \times 10^{13} G$, or in any application where the enhancement or suppression of SBS may be important.

1. Introduction

The recent growing interest of quantum plasmas [1, 2] is due to its diverse and potential applications in metallic and semiconductor nanostructures such as: metallic nano particles, metallic thin films, spintronics, nanotubes and quantum dots etc [3]. Quantum plasmas are also very common in various astrophysical environments such as: planetary interiors, in white dwarf stars, neutron stars (NS), magnetars and pulsars [4] etc. NS mostly composed of iron, oxygen,carbon and helium nuclei, [5] are dense enough ($\geqslant 10^{30}$ cm^{-3}) to be treated as quantum systems. The existence of Neutron stars (NS) was initially predicted by Landau [6], later these were categorized as pulsars by Hewish *et al* [7]. The Surface magnetic field of neutron stars can have strengths of around $10^{11} \sim 10^{13} G$ whereas the core may have even higher values and can be $\geqslant 10^{15} G$ [4, 8, 9]. The rotation of the star contributes to super strong magnetic field SSH by raising the order by $10^3 - 10^4 G$ [10]. The super strong magnetic (SSH) field in Fermi gas may lead to various interesting features such as fractional quantum Hall effect, which was described theoretically in [11] and observed experimentally in GaAs heterostructures [12], SSH field may lead the Fermi gas to attain a superconducting state [13] etc. The effects of SSH field in quantum plasmas may also be relevant in further developments of modern technology (e.g. metallic and semiconductor nanostructures) [14–16] and in the development of next generation intense laser-solid density matter experiments.

It was shown by Landau [17] that SSH field leads to the Landau diamagnetism owing to quantization of the gyratory motion of Fermi electrons, also known as the Landau quantization (LQ), and the intrinsic or spin magnetic moment of electrons gives rise to Pauli paramagnetism. In this scenario, Hussain *et al* [18] pointed out that both LQ and spin effects may introduce interesting outcomes in the kinetic treatment of the quantum plasmas.Quite recently, Brodin *et al* [19] have developed a quantum kinetic theory of plasmas while taking into account Pauli Hamiltonian based spin dynamics and Hartree–Fock exchange effects, new quantum theories and the associated applications were presented in this paper. A modified kinetic model for the plasma embedded in a relativistically strong magnetic field is formulated in [20], where the usual relativistic γ factor is replaced by an energy operator (in Vlasov equation) to depict that the energy eigenstates in a magnetic field can be calculated as eigenfunctions of this operator. Landau level based chiral kinetic theory for slowly varying magnetic field is developed in [21] to show that under appropriate conditions, the transverse conductivity is inversely proportional to the relaxation time. Recently kinetic model is employed to study the impact of SSH field via LQ on the shielding potential in an ion acoustic mode around a test charge [22], where LQ is found to enhance the Debye shielding potential, while a decreasing trend on the wake potential is highlighted.

In this context, the investigation of dense plasmas in the presence of SSH has achieved considerable attention in last few decades [5, 23–25], which made it possible to calculate the spectrum and polarization of electromagnetic wave (EMW) formed in an extended, partially ionized hydrogen atmosphere in the photoemission region of NS [26].

It is also well known from the literature that magnetized compact objects like pulsars and magnetars may produce strong EMWs: the pulsars produce bright radio emission, while magnetars may generate fast radio bursts [27, 28]. For a middle aged neutron star of about $10^4 - 10^6$ years old and $B \leqslant 10^{13}$ G the spectrum of thermal emission from a NS related to the thermal flux was investigated by Potekhin *et al* [23]. Consequently, the SSH field in these objects has opened new doors of laser-plasma interactions [29], which may lead to both useful nonlinearities. As well as the risk of harmful scatterings in implosion-type experiments. The EMWs scattering in the atmosphere of pulsars was considered in [30] to conclude that the induced scattering influences the spectrum of radio waves in pulsars.

The interaction of EMW with plasma is an important research area, in theory and experiments, due to its wide range of applications such as: laser induced fusion, charged particle acceleration in ionospheric situations which may lead to new radiation sources [31–36]. This interaction may have importance for beat-wave accelerator [37], where two EMW beams of different harmonics are used to resonate and excite electron plasma waves, which in turn accelerates electrons to high speeds. In such scenarios it is expected that the modulational three wave decay and filamentation instabilities of EMWs can be described by appropriate nonlinear Schrödinger equations to investigate stimulated Brillouin scattering (SBS) instabilities. It may be recalled that the scattering of the EMWs at an ion time scale is known as SBS, which can be observed upto some critical density n_c. The present active space experiments using high-frequency radio waves predict the SBS phenomena in the ionospheric plasma [38], It is noted here that SBS occurs in both classical and degenerate plasmas and has found applications in laser fusion [39, 40], and fiber optics [41] etc. The SBS and its associated three wave decay, modulational and filamentational instabilities may serve as an important tool to investigate various acoustic modes. However, the scattering of EMWs from electron/ ion plasmas can be either toxic due to loss of energy from stimulated scattering [42–44], or may serve as an important instability for the construction of ultra-high-power plasma-based parametric amplifiers [45]. High-intensity laser driven instabilities are of much interest in inertial confinement fusion (ICF) [46], accelerator physics [47, 48], nonlinear optics [49] and physics of the atmosphere [50].

The scattering instabilities of EMW in unmganetized, quantum plasmas was discussed in [51]. Recently, Rozina *et al* [52] have considered SBS instability of large amplitude EMW propagating through an unmagnetized quantum electron-ion plasma. It is important to note here that only a few authors have considered the effect of a super strong magnetic field on SBS [53–55], while some of the work was presented through simulation studies [56, 57]. The scattering of laser from a strongly magnetized plasma to account for SBS was considered using Particle-In-Cell (PIC) [58] simulations and where the authors claimed that their results are applicable to strongly, magnetized laser-confinement experiments. However to the best of our knowledge scattering instabilities of EMWs in the presence of quantized magnetic pressure, arising due to SSH field, has not been considered yet.

Recently, a model was presented in [52] to address the scattering mechanism of EMW in an unmagnetized electron ion plasma with quantum corrections. It was found in this paper that the quantum effects, involving Fermi pressure and quantum correlations, stabilizes the scattering instabilities. In our present work we shall revisit this study to check the signatures of strong magnetic field on the SBS instability by taking into account Landau quantization. The paper is organized as follows: a brief overview of Landau Quantization is given in section 2. The nonlinear evolution equations for quantized magnetosonic waves (QMW) and high frequency EMWs are developed in sections 3 and 4, respectively. In section 5, the nonlinear coupling of high frequency EMWs with QMWs is considered to obtain the growth rates of the magnetized stimulated Brillouin scattering (MSBS) instability. Numerical analysis and conclusions are given in sections 6 and 7 respectively.

2. The Landau theory of magnetization

In classical plasmas the Lorentz force $\frac{e}{c}(V \times H)$ acts in a plane perpendicular to the magnetic field, hence no work is produced. However, it was shown by Landau [6] that this situation changes drastically in quantum theory of magnetism. The magnetization of fermions in H field give rise to two magnetic effects, namely Pauli paramagnetism due to the spin motion of electrons and Landau diamagnetism due to the quantization of their gyratory motion, known as Landau quantization. The Fermi electrons under the influence of strong magnetic field gyrates in circular orbits in a plane perpendicular to the applied magnetic field $\sim H_0\hat{z}$, hence their motion may be resolved into two components [6, 17, 59] (i). One along the direction of magnetic field, this motion is uniform and is not quantized with the associated longitudinal component of energy, $E_x = \frac{p_z^2}{2m_e}$(p_z is the kinetic momentum along the direction of applied field), (ii). Second is the transverse component in a plane perpendicular to H_0, causing the fermions to rotate in circular orbits, just like for the case of a linear harmonic oscillator moving with cyclotron frequency $\omega_c(= \frac{eH_0}{m_e c})$, and here the corresponding energy spectrum is discrete due to quantum effects [60]. In this scenario, we use the work of Tsintsadze *et al* [4], who showed that in the presence of strong magnetic field, if the particle also has spin, the intrinsic or spin magnetic moment of the fermi particles interacts directly with the magnetic field, accordingly the total electron energy levels $\varepsilon_e^{l,\sigma}$ was expressed as

$$\varepsilon_e^{l,\sigma} = \frac{p_z^2}{2m_e} + (2l + 1)\beta_B H_0 + \sigma H_0 \beta_B, \tag{1}$$

where the 1st term on the right hand side is the energy in the direction of ambient magnetic field, let us say $z - axis$, p_z is the associated momentum, the second term appears due to the Landau quantization, which contributes the quantization of gyratory motion of fermions around magnetic filed, whereas the last term represents the spin motion of fermi electrons, known as Pauli paramagnetism [60]. Here $l(= 0, 1, 2, \ldots\ldots)$ and $\beta_B(=\frac{|e|\hbar}{2m_e c})$ are the orbital quantum number and Bohr magnetron respectively, $\hbar$ is the Planck's constant divided by $2\pi$and σ is the operator to the z direction and describes the spin orientation $s = \frac{\sigma}{2}(\sigma = \pm 1)$. From the expression (1) one sees that the energy spectrum of the electrons consists of the lowest Landau level $l = 0$, $\sigma = -1$ and pair of degenerate levels with opposite polarization $\sigma = 1$, thus each value with $l = 0$ occurs once and twice with $l \neq 0$. Therefore in the non-relativistic limit ε_e^l reads as [61, 62]

$$\varepsilon_e^{l,\sigma} = \varepsilon_e^l = \frac{p_z^2}{2m_e} + 2l\beta_B H_0 \tag{1a}$$

Further, the authors [61] have calculated the influence of strong or super strong magnetic field on the thermodynamic properties of a Fermi gas, having magnetic energy more than the fermi energy i.e. $\hbar\omega_{ce} > \varepsilon_{F_e}(=\frac{(2\pi^2)^{2/3}\hbar^2 n_e^{2/3}}{2m_e})$. Specifically, Tsintsadze *et al* use equation (1)) [62] (see page.8 of this Ref.) and employ the Kelly distribution function to derive the consequent quantized magnetic pressure P_e of a degenerate fermi electron gas in a direction perpendicular to the external H_0 field as

$$P_e = \frac{\hbar\omega_{ce}}{3} n_e, \tag{2}$$

where n_e is the electron number density. It may be noted here that in order to see the impact of quantized magnetic pressure [shown in equation (2)] on the Brillouin scattering instability, we shall only consider only the spatial variations perpendicular to the H_0 field [63, 64]. It can also be noted here that the inequality, $\hbar\omega_{ce} > \epsilon_F$, is satisfied provided $H_0 > 10^9 G$ at $n_e \sim 10^{24}\ \mathrm{cm}^{-3}$. Such high magnetic filed may exist in semiconductors as an example $\sim 10^7 G$ is considered by [65] in an n-Type GaAs semiconductor$\sim 2.3 \times 10^8 G$ is mentioned in [66] for an iron-cobalt alloy ($Fe_{65}Co_{35}$), while astrophysical compact like pulsars, magnetars may have even higher magnetic filed strength i.e. $H_0 \gtrsim \sim 10^{12} - 10^{13} G$.

3. Quantized magnetosonic waves (QMWs)

In this section we investigate the MSBS, while taking into account LQ, by employing the quantum fluid model, which may serve as striking substitute to model and simulate the dynamics of fermi electron at nanoscale,e.g., quantum fluid models involving both spin and spinless species are reviewed in [67]. Let us recall that the MSBS arises due to the nonlinear scattering of EMWs through strongly magnetized, quantized, degenerate electron ion-plasma at the ionic time scale. For our investigations, we formulate the governing differential equation of QMWs in the presence of SSH field and thus include the associated quantized magnetic pressure shown in equation (2). We assume that the electrons are quantized and degenerate, while ions are treated as classical due to their heavy mass, whereas the electron inertia is taken to be negligible. We consider the geometry such that the total SS magnetic field is in the $z - direction$, i.e. H_0 and consider propagation in the $x - direction$ only i.e. $\nabla = \nabla_x$. For present analysis the basic set of equations includes the equations of motion [24, 25, 51] of inertialess Fermi electrons and inertial classical ions, respectively

$$\frac{m_e n_e}{2}\nabla_x|V_e|^2 = -n_e e\left(\mathbf{E} + \frac{1}{c}(\mathbf{V}_e \times \mathbf{H})\right)_x - \nabla_x P_e + F_{Qe}, \tag{3}$$

$$m_i n_i \frac{\partial V_{ix}}{\partial t} = n_i e\left(\mathbf{E} + \frac{1}{c}(\mathbf{V}_i \times \mathbf{H})\right)_x, \tag{4}$$

We note here that the term on the left hand side of equation (3) is Ponderomotive term on the ion time scale and contains the electronic mass m_e. Where $E(H)$ are the electric (magnetic) fields, c is the light speed, m_i is the mass of ions and n_e and n_i are the number densities of electrons and ions respectively, P_e is the electron magnetic pressure, defined in equation (2) and $F_{Qe} = \frac{\hbar^2}{2m_{e,i}}\nabla_x\frac{1}{\sqrt{n_{e,i}}}(\nabla_x^2\sqrt{n_{e,i}})$ is the quantum tunneling effect of electrons. The electric and magnetic field oscillations can be expressed through scalar ϕ and vector potentials A as

$$\mathbf{E} = -\nabla\phi - \frac{1}{c}\frac{\partial \mathbf{A}}{\partial t}\text{and } \mathbf{H} = \boldsymbol{\nabla} \times \mathbf{A}. \tag{5}$$

We can show that the leading order electrons i.e. $n_e m_e \frac{\partial \mathbf{V}_e}{\partial t} = -n_e eE$, gives rise to the momentum of electrons due to the electromagnetic wave from equation (5) as

$$m_e \mathbf{V}_e = -\frac{e_{e,i}\mathbf{A}_\perp}{c} = \mathbf{p}_e, \tag{6}$$

here $A_\perp$ is the vector potential perpendicular to the magnetic field and p_e is the electron momentum associated with the vector potential. In addition to the above equations (3)–(6) we also include, here the continuity equation for ions and Maxwell's equations, for low frequency waves, in order to have a complete set of equations

$$\frac{\partial n_i}{\partial t} + n_i\nabla.V_i = 0, \tag{7}$$

$$\boldsymbol{\nabla} \times \mathbf{H} = \frac{4\pi}{c}\mathbf{J}, \tag{8}$$

$$\boldsymbol{\nabla} \times \mathbf{E} = -\frac{1}{c}\frac{\partial}{\partial t}\mathbf{H}, \tag{9}$$

where $J = e(n_i V_i - n_e V_e)$ is the current density of plasma species.

Along with Ohm's Law

$$\mathbf{E} = -\mathbf{v} \times \frac{1}{c}\mathbf{H} \tag{10}$$

By using equations (8) and (9) Ohm's law can be written as

$$\frac{\partial \mathbf{H}}{\partial t} = \boldsymbol{\nabla} \times (\mathbf{v} \times \mathbf{H}), \tag{11}$$

Further by adding equations (3), (4) and using (8) we obtain a quantum nonlinear MHD equation for the ions,

$$m_i\frac{\partial V_{ix}}{\partial t} = -\frac{m_e}{2}\nabla_x|V_e|^2 - \frac{1}{n_0}\nabla_x\left(P_e + \frac{1}{8\pi}H^2\right) + \frac{\hbar^2}{2m_e}\nabla_x\frac{1}{\sqrt{n_e}}(\nabla_x^2\sqrt{n_e}), \tag{12}$$

Here we assume the quasi neutrality condition $n_0 = n_{0e} = n_{0i}$. Let us now consider the oscillating form of equation (12)

$$\frac{\partial \delta V_i}{\partial t} = -\frac{m_e}{2m_i}\nabla_x\delta|V_e|^2 - \frac{1}{m_i n_0}\nabla_x(\delta P_e + \frac{H_0^2}{4\pi}\frac{\delta H_z}{H_0}) + \frac{\hbar^2}{4m_e m_i}\nabla_x\left(\nabla_x^2\frac{\delta n_e}{n_0}\right), \tag{13}$$

Where The oscillating magnetic pressure can be obtained from equation (2),

$$\delta P_e = P_{0e}\left(\frac{\delta H_z}{H_0} + \frac{\delta n_e}{n_{0e}}\right), \tag{14}$$

where all terms of the form δa are fluctuating quantities. From equation (2) we get $P_{0e} = \frac{\hbar\omega_{ce0}}{3}n_{0e}$ which is the equilibrium magnetic pressure of electrons. Now in order to express SSH field oscillations into density perturbations of Fermi electrons, we get from equation (11)

$$\frac{\partial \delta H_z}{\partial t} = H_0 \nabla . V_i \text{or} \frac{\delta H_z}{H_0} = \frac{\delta n_e}{n_0}. \tag{15}$$

Differentiating continuity equation (7) once w.r.t. t and substituting (13) alongwith equations (14), (15) and eliminating all perturbed quantities in favour of $\delta n(=\delta n_i \approx \delta n_e)$, we get

$$\left[\frac{\partial^2}{\partial t^2} + \frac{\hbar^2}{4m_e m_i}\nabla_x^4 - (V_A^2 + C_{He}^2)\nabla_x^2\right]\frac{\delta n}{n_0} = \frac{e^2}{2m_i m_e c^2}\nabla_x^2 |A_\perp|^2, \tag{16}$$

where $V_A(=\frac{H_0}{\sqrt{4\pi m_i n_i}})$ is the Alfven velocity, $C_{He}(=\sqrt{\frac{P_{0e}}{m_i n_{i0}}})$ is the quantized magneto ion velocity, duly modified by Landau quantization due to SSH field. Equation (16) is the required evolution equation of quantized magnetosonic wave (QMW) in the presence of SSH field to derive the MSBS instability. We see that equation (16) reduces to the case of a quantized ion acoustic wave when $C_{He}^2 >> V_A^2$ investigated in [25]. If we ignore the nonlinear term on the right hand side of equation (16) and apply the plane wave solution by taking $\delta n = \exp(ikx - i\Omega t)$ we get the following linear dispersion relation for QMWs

$$\Omega^2 = \frac{\hbar^2 k^4}{4m_e m_i} + (V_A^2 + C_{He}^2)k^2 \tag{17}$$

4. Pump EM waves

In order to study the nonlinear interaction of EMWs with plasma under consideration, we shall establish the nonlinear differential equation of pump EMW in the presence of electron density perturbations. Here we assume only one dimensional propagation of EMWs in the Cartesian coordinate system i.e. $x - axis$ and make use of Maxwell equations (6), (8) (9), (10) to obtain the following equation for the electromagnetic pump wave in terms of the EMW packet, having complex amplitude

$$\left(\frac{\partial^2}{\partial t^2} - c^2\nabla^2 + \omega_{pe}^2\right)\mathbf{A}_\perp + \omega_{pe}^2\frac{\delta n}{n_0}\mathbf{A}_\perp = 0, \tag{18}$$

here $A_\perp = A_{0\perp}e^{i(k_0 x - \omega_0 t)}$ with $A_{0\perp}$ which is the amplitude in terms of vector potential and $\omega_{pe} = \sqrt{4\pi n_{e0}e^2/m_e}$ is the electron plasma frequency. To study the MSBS instability equation (18) is the required differential equation of pump EMWs.

5. MSBS instability

Three wave interaction

We use the standard procedure [51] to investigate the nonlinear interactions of pump EMWs with QMW to account for MSBS instability. For our investigations, we couple equations (16) and (18) by using phasor matching technique to get nonlinear dispersion relations of MSBS. In this scenario, the nonlinear scattering of pump EMWs (k_0, ω_0) having oscillations $\exp(ik_0 x - i\omega_0 t) + c.c$ from strongly magnetized degenerate ion waves with density fluctuations $\frac{\delta n}{n_0} = N_s = \hat{N}_S \exp i(kx - \Omega t)$ for QMWs produces two side bands namely upper and lower sidebands, $A_{\perp 0\pm}\exp(ik_\pm x - i\omega_\pm t)$, respectively. The sidebands involve the wave vectors $k_\pm = k \pm k_0$ and frequencies $\omega_\pm = \Omega \pm \omega_0$. Consequently the vector potential, $A_\perp$, can be resolved into upper and lower sidebands [51, 52]

$$A_\perp = A_{0\perp+}\exp(-i\omega_0 t + ik_0 x) + A_{0\perp-}\exp(i\omega_0 t - ik_0 x) + \sum A_{\pm\perp}\exp(-i\omega_\pm t + ik_\pm x), \tag{19}$$

here the subscript 0 and $\pm$ shows the pump EMW and EMW upper and lower sidebands arising due to the nonlinear interaction of the pump with the QMWs. Next, we simply apply the Fourier transform mentioned above to equation (18) and collect the same phasor terms on both sides to get

$$G_\pm A_{\perp\pm} = \hat{N}_S\omega_{pe}^2 A_{\perp 0\pm}, \tag{20}$$

where $G_\pm$ is the upper and lower side band defined as

$$G_\pm = \omega_\pm^2 - c^2k_\pm^2 - \omega_{pe}^2 \equiv \pm 2\omega_0(\Omega - kv_g \mp \delta), \tag{21}$$

here $\omega_0^2 = \omega_{pe}^2 + c^2k_0^2$ is the frequency of the pump EMWs, $\delta = \frac{k^2c^2}{2\omega_0}$ is the small frequency shift, $v_g(=k_0c^2/\omega_0)$ is the group velocity of EM pump wave. It is worth mentioning here that while deriving equation (20), we have used $A_{\perp 0+} = A_{\perp 0}$ and $A_{\perp 0-} = A_{\perp 0}^*$, where asterisk is the complex conjugate, also in equation (21) we have assumed that the frequency of pump EMW (ω_0) is large as compared to the QMW frequency i.e. $\Omega \ll \omega_0$.

Similarly by applying the Fourier transforms and collecting the same phasor terms on both sides of equation (16), we get

$$\left(\Omega^2 - \frac{\hbar^2 k^4}{4m_e m_i} - (V_A^2 + C_{He}^2)k^2\right)\hat{N}_s = \frac{e^2k^2}{2m_i m_e c^2}(A_{\perp 0}A_{\perp -} + A_{\perp 0}^{\star}A_{\perp +}). \tag{22}$$

Making use of equation (20), we may obtain

$$\left(\Omega^2 - \frac{\hbar^2 k^4}{4m_e m_i} - (V_A^2 + C_{He}^2)k^2\right)\frac{G_{\pm}A_{\perp\pm}}{\omega_{pe}^2 A_{\perp 0\pm}} = \frac{e^2k^2}{2m_i m_e c^2}(A_{\perp 0}A_{\perp -} + A_{\perp 0}^{\star}A_{\perp +}),$$

or

$$S_M = \frac{\omega_{pe}^2 e^2 k^2}{2m_i m_e c^2}\sum\frac{|A_{\perp 0}|^2}{G_{\pm}}, \tag{23}$$

where $S_M = \Omega^2 - \frac{\hbar^2 k^4}{4m_e m_i} - (V_A^2 + C_{He}^2)k^2$. Equation (23) is the required dispersion relation for investigating both three wave decay and modulation instabilities of MSBS of parametrically coupled large amplitude EMWs with degenerate electron-ion plasma in the presence of SSH field. For three wave decay interactions, we shall consider the lower side band to be resonant ($G_- = 0$) while the upper side band is supposed to be off-resonant ($G_+ \neq 0$) in equation (23). Then by using coinciding roots [52],

$$\Omega - kv_g + \delta = i\gamma_{MSBS}, \tag{24}$$

and

$$\Omega = \Omega_{MSBS} + i\gamma_{MSBS}, \tag{25}$$

where $\Omega_{MSBS}^2 = \frac{\hbar^2 k^4}{4m_e m_i} + (V_A^2 + C_{He}^2)k^2$ we may obtain the growth rate of MSBS scattering instability by using equation (21) and equation (23)

$$\gamma_{MSBS} = \frac{\omega_{pe} ek|A_{\perp 0}|}{2\sqrt{2\Omega_{MSBS}\omega_o m_i m_e}\, c}, \tag{26}$$

It is clear from the above equation that SSH field suppresses the growth rate of MSBS instability via C_{He} and V_A along with Bohm term, whereas γ_{MSBS} is found to be a direct function of vector potential $A_{\perp 0}$ of EM waves.

Modulational Instability

In order to investigate MSBS via the modulational instability, we now take both upper and lower sidebands or $G_{\pm} \neq 0$ in equation (23) and obtain

$$S_M((\Omega - kv_g)^2 - \delta^2) = \frac{\delta\omega_{pe}^2 e^2 k^2\, |A_{\perp 0}|^2}{2\omega_o m_i m_e c^2}. \tag{27}$$

The maximum growth rate $\gamma_{MSBS}^{\max}$ of MSBS instability can be obtained from equation (27) by neglecting the the square of the nonlinear correction shift on the frequency of EM waves i.e. $\delta^2 = 0$ and by using the matching roots $\Omega - kv_g + \delta = i\gamma_{MSBS}^{\max}$

$$\gamma_{MSBS}^{\max} = \left(\frac{\delta\omega_{pe}^2 e^2 k^2\, |A_{\perp 0}|^2}{2m_i m_e c^2 \omega_0 \Omega_{MSBS}}\right)^{1/3}, \tag{28}$$

We can further investigate equation (28) for two limiting cases (i). if $\Omega \ll \Omega_{MSBS}$ then

$$\Omega = kv_g \pm \left(\delta^2 - \frac{1}{\Omega_{MSBS}^2}\frac{\delta\omega_{pe}^2 e^2 k^2}{2m_e mic^2\omega_0}\, |A_{\perp 0}|^2\right)^{1/2}, \tag{29}$$

equation (29) leads to an oscillatory modulational instability [52], provided $|A_{\perp 0}| > \frac{c\Omega_{MSBS}}{ke\omega_{pe}}\sqrt{2m_e m_i \delta\omega_0}$. (ii). If $kv_g = 0$, then we may have from equation (27)

$$\Omega^2 = \frac{(\Omega_{MSBS}^2 + \delta^2)}{2} \pm \frac{1}{2}\sqrt{(\Omega_{MSBS}^2 - \delta^2)^2 + \frac{2\delta\omega_{pe}^2 e^2 k^2}{m_i m_e c^2 \omega_0}\, |A_{\perp 0}|^2}. \tag{30}$$

equation (30) represents the oscillatory modulational instability [52] in strongly magnetized quantum plasma to conclude that the oscillatory modulational instability decreases with the increase of SSH field. The analytical results calculated in equations (26), (28) and (30) shows that the quantized SSH field modifies the characteristics of Brillouin scattering instability.

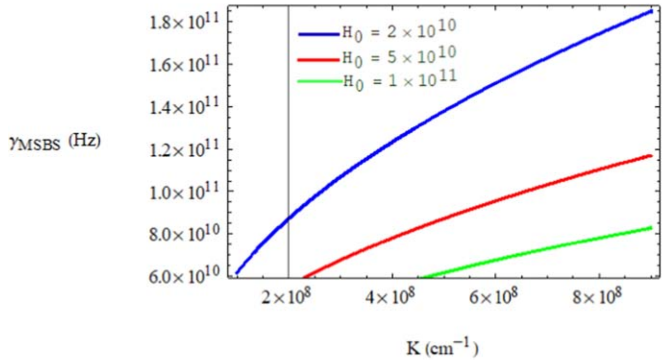

Figure 1. Growth rates of MSBS (γ_{MSBS}) instability (equation (26)) versus the wave number (k) for $\mathbf{n}_{e0} = 3 \times 10^{24}$ cm^{-3}, $A_0 = 0.03V$, $k_0 = 6.28 \times 10^7$ cm^{-1} for different values of SSH field $H_0 = 2 \times 10^{10}G$ (blue curve), $5 \times 10^{10}G$ (red curve) and $1 \times 10^{11}G$ (green curve).

Table 1. Comparison of different physical plasma parameters for different values of SSH field (H) for: $n_{e0} = 3 \times 10^{24}$ cm^{-3}, $A_0 = 0.03V$, $k_0 = 6.28 \times 10^7$ cm^{-1} and $k = 10^6$ cm^{-1}.

Sr. No.	Physical parameters	$H = 2 \times 10^{10}G$	$H = 5 \times 10^{10}G$	$H = 1 \times 10^{11}G$
1	$C_{He}(cms^{-1})$	1.21×10^7	1.91×10^7	2.71×10^7
2	$V_A(cms^{-1})$	2.52×10^9	6.30×10^9	1.26×10^{10}
3	$\Omega_{MSBS}(Hz)$	2.52×10^{15}	6.30×10^{15}	1.26×10^{16}
4	$\gamma_{MSBS}(Hz)$	6.16×10^9	3.90×10^9	2.75×10^9
5	$\gamma_{MSBS}^{max}(Hz)$	2.42×10^6	1.32×10^6	8.32×10^5
6	$\Omega(Hz)$	2.52×10^{15}	6.30×10^{15}	1.26×10^{16}

6. Results and discussion

To see more clearly the impact of SSH field on the dispersive characteristics of the MSBS instability of EMWs, we analyze Equations (26), (28), (30) numerically. For this purpose, we choose the typical plasma parameters in the atmosphere of neutron stars in cgs system of units: $H_0 \simeq 10^{10} - 10^{12}G$ (in the surface crust of neutron star NS) [68], $n_{e0} = 3 \times 10^{24} cm^{-3}$ $c = 2.99 \times 10^{10} cms^{-1}$, $m_e = 9.1 \times 10^{-28}g$, $m_i = 1.67 \times 10^{-24}g$, $e = 4.8 \times 10^{-10}$*stat coloumb*, $\hbar = 1.05 \times 10^{-27}$ cm$^2gs^{-1}$ and $k_B = 1.3807 \times 10^{-16} cm^2gs^{-2}K^{-1}$. The prerequisite condition for the magnetic field quantization to occur i.e, $\hbar\omega_{ce} > \varepsilon_{F_e}$ is found to be satisfied at $H_0 \sim 2 \times 10^{10}G$. For the choice of the electron density used here, the cutoff frequency of EM waves turns out to be $\omega = 9.7 \times 10^{16}Hz$, so the present model is valid for the propagation of EM waves having frequencies $> 9.7 \times 10^{16}Hz$ i.e. X-rays, Gamma rays etc. We choose high frequency soft x-rays as pump wave, with typical frequency $\omega = 10^{17}Hz$ and scale length $\lambda = 10^{-7}cm$. Then to examine how the SSH filed via C_{He} may alter the scattering growths of MSBS via three wave decay (γ_{MSBS}) and modulational instabilities (γ_{MSBS}^{max}), we assume $H_0 = 2 \times 10^{10}G$, $n_{e0} = 3 \times 10^{24}$ cm^{-3}, $A_{\perp 0} = 0.03V$, $k_0 = 6.28 \times 10^7$ cm^{-1} and $k = 10^6$ cm^{-1} to obtain $C_{He} = 1.2 \times 10^7 cms^{-1}$, $\Omega_{MSBS} = 2.5 \times 10^{15}Hz$, $\gamma_{MSBS} = 6.1 \times 10^9 Hz$, $\gamma_{MSBS}^{max} = 2.42 \times 10^6 Hz$ and $\Omega = 2.5 \times 10^{15}$ Hz. However by changing $H_0 = 1 \times 10^{11}G$ while keeping all other parameters same, we obtain $C_{He} = 2.7 \times 10^7$ cms^{-1}, $\Omega_{MSBS} = 1.2 \times 10^{16}Hz$, $\gamma_{MSBS} = 2.7 \times 10^9 Hz$, $\gamma_{MSBS}^{max} = 8.3 \times 10^5$ Hz and $\Omega = 1.2 \times 10^{16}$ Hz. This analysis clearly admits that the SSH field is suppressing the scattering growths of MSBS, while the scattering growth is increasing via modulational frequency (Ω), provided $kv_g = 0$.

For the sake of clarity we have included table 1, which shows that an increase in the SSH field leads to an increase in the values of C_{He}, V_A and Ω_{MSBS} and shows the corresponding reductions in the MSBS frequencies through decay and maximum modulational instabilities, while an upshift in the modulated frequency Ω is presented in the last row of the table.

Next, we display our analytical results graphically by keeping the number density fixed in all plots and assume initially that the wave number of QMW is greater than that of pump soft x-rays i.e. $k(= 10^7 - 10^8)cm^{-1} > k_0$, to have the backward [69] scattering. Equation (26) is plotted in figure 1 to see that at $H_0 = 10^{11}G$ and $k = 10^8$ cm^{-1} the frequency offset $\sim$80GHz as a result of backward MSBS instability of soft x-rays (γ_{MSBS}). Next, in the case of modulational instability, equation (28) is plotted in figures 2(a), (b) for the same SSH field trip as in figure 1 to see the maximum reduction in backward/forward scatterings of soft x-rays (as a function of SSH field). Figure 2(a) shows frequency offset $5.5 \times 10^7 Hz$ in backward and comparatively

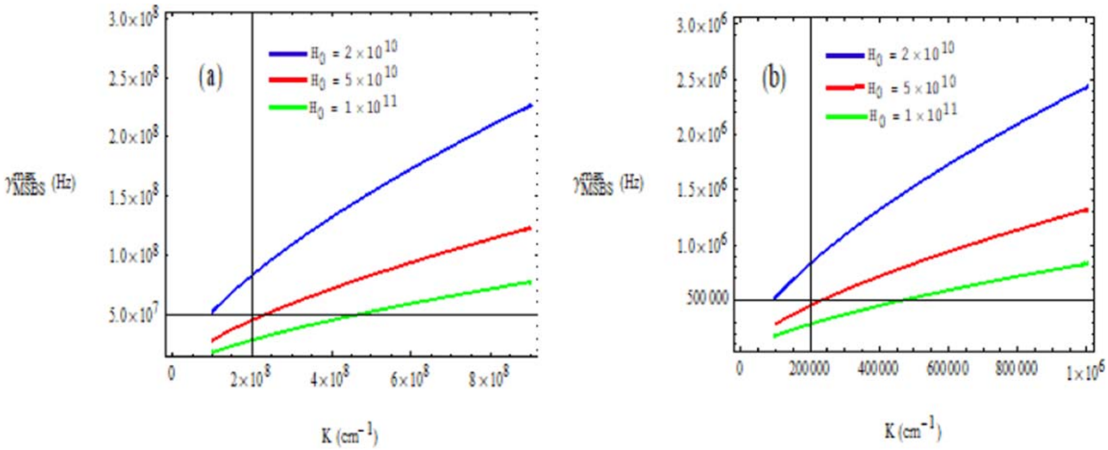

Figure 2. Frequency shift via the maximum growth rate of MSBS modulational instability of soft x-rays (γ_{MSBS}^{max}) (equation (28)) versus the wave number (k) that are scattered off electron density perturbations for the same set of parameters as in figure 1. The subplot (b) is plotted for the forward scattering of MSBS i.e. $k < k_0$. The other parameter values are same as in subplot (a).

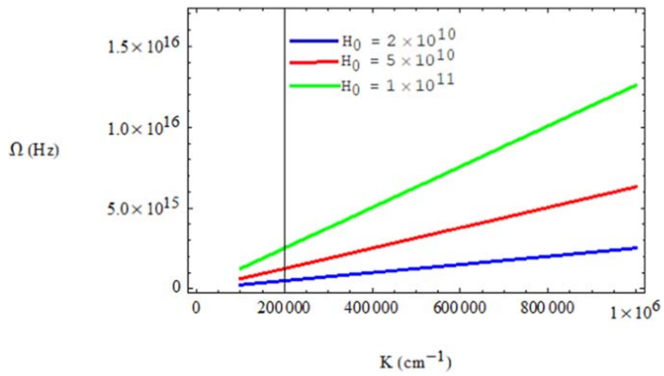

Figure 3. Modulational MSBS frequency (Ω) (shown in equation (30)) versus the wave number (k) for different values of $H_0 = 2\times10^{10}G$ (blue curve), $5\times10^{10}G$ (red curve) and $1\times10^{11}G$ (green curve) in figure 3 while keeping other parameters same as in figure 2(b).

more suppression of MSBS can be seen from figure 2(b) i.e $\sim10^6 Hz$ in case of forward scattering at 10^6 cm^{-1}, which is a noticeable forward suppression of magnetic Brillouin scattering instability of soft x-rays as a function of SSH field. Next, we use equations (30) for the upper root ($+ve$) only for the parameter values given above. These results are shown in figure 3, and it is seen that the increasing frequency shifts of soft x-rays as a function of SSH field while keeping all parameters same as in figures 2(b). From figure 3, we notice that the frequency of modulation is always up shifted in forward direction i.e. it increases as we go on increasing the values of quantized SSH field even for the EMWs of very small amplitude ($A_{\perp 0}$), however SSH field variations does not effect the modulation instability in backward direction. We also note that the negative root in equation (30) gives only imaginary values and hence does not lead to any modulational instability.

7. Conclusion

To conclude, we have used Landau magnetization of Fermi electron gas, to investigate the impact of quantized magnetic pressure on the nonlinear scattering process of high frequency EMWs from quantized, degenerate electron ion plasma. QMHD model is obtained to get the governing differential equation of QMWs and is found to be modified by the magnetic field quantization effects, appearing through the quantized ion acoustic (C_{He}) and Alfven (V_A) speeds, provided $\hbar\omega_{ce} \geqslant \epsilon_{F_e}$, which is the condition for the existence of a super strong magnetic field. Next, by using Maxwell equations, the governing nonlinear differential equation equation (18) of pump EMWs is derived. Then the phasor matching technique is followed to couple pump EMW with QMWs, as a result the governing dispersion relation of MSBS is obtained, which is further discussed for three wave decay and modulational instabilities, the associated growth rates are calculated. Maximum scattering rate of MSBS instability, γ_{MSBS}^{max}, is obtained by ignoring the nonlinear correction shift on the frequency of EMWs to demonstrate that the quantized SSH field suppresses the growth rate of MSBS. Maximum suppression in the frequency shifts of MSBS is observed in case of forward scatterings of modulated EMWs. On the other hand, for a particular condition ($kv_g = 0$) the growth rate of modulated EMWs is found to increase as a function of SSH field even for the EMWs of very small amplitude. Our results could be interesting because, we have shown that for the fixed density concentration of electrons, the SSH field alone may alter the scattering rates of EMWs from quantum electron ion plasma, as is evident from our main results equations (26) (28)–(30), whereas the quantum dispersive effects in literature are function of fermion density usually. The obtained results are checked numerically for the soft x-rays of suitable frequency range. Numerical and graphical results support our theoretical analysis and conclusions. The compression and the enhancement in the growth rate of MSBS instability may be useful for high-intensity laser experiments with strong applied or self-generated magnetic fields. Due to the present possibility of generating strong magnetic field in laboratory [70], our results can be valid for laboratory plasmas as well to get fruitful results via MSBS. MSBS may also provide valuable information about the density oscillations in cold microplasma and astrophysical settings, in a manner similar to plasma diagnostics in the Earth's ionosphere [71]. As a take home message this study can be extended to see the effect of MSBS at kinetic scales.

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Data availability statement

No new data were created or analysed in this study.

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References

[1] Bonitz M *et al* 2003 Theory and simulation of strong correlations in quantum Coulomb systems *J. Phys. (A: Mathematical and General)* **36** 5921
[2] Manfredi G 2005 How to model quantum plasma *Fields Inst. Commun.* **46** 263
[3] Shukla P K and Eliasson B 2009 Nonlinear aspects of quantum plasma physics :nanoplasmonics and nanostructures in dense plasmas *Plasma and Fusion Research* **4** 32 arXiv:0906.4051
[4] Tsintsadze N L and Tsintsadze L N 2012 Relativistic thermodynamics of magnetized fermi electron gas physics arXiv:1212.2830
Tsintsadze L N 2010 Quantization and excitation of longitudinal electrostatic waves in magnetized quantum plasmas *AIP Conf. Proc.* **1306** 89–102
[5] Rozina C, Tsintsadze N L and Tsintsadze L N 2020 Magnetic field quantization in pulsars *J. Plasma Phys.* vol 86 (Cambridge: Cambridge University Press) 905860211 (https://doi.org/10.1017/S0022377820000252)
[6] Landau L D and Lifshitz E M 1998 *Statistical Physics* (Oxford: Butterworth-Heinemann) Part 1
Landau L D and Lifshitz E M 1948 *Quantum Mechanics* (Moscow: TTL)
[7] Hewish A, Bell S J, Pilkington D H, Scott P F and Collins R A 1968 Observation of a rapidly pulsating radio source *Nature* **217** 709
[8] Tsintsadze N L, Rozina C, Ruby R and Tsintsaze L N 2018 Jeans anisotropic instability *Phys. Plasma* **25** 073705
[9] Shapiro S L and Teukolsky S A 1981 *Black Holes, White Dwarfs, and Neutron Stars* (New York: Wiley)
[10] Bisnovati-Kogan G S and Astron Z 1970 *The Explosion of a Rotating Star As a Supernova Mechanism* **47** 813
[11] Loughlin R B 1983 Anomalous quantum hall effect: an incompressible quantum fluid with fractionally charged excitations *Phys. Rev. Lett.* **50** 1395
[12] Tsui D C, Stormer H L and Gossard A C 1982 Two-dimensional magnetotransport in the extreme quantum limit *Phys. Rev. Lett.* **48** 1559
[13] Tsintsadze N L and Tsintsaze L N 2012 Relativistic thermodynamics of magnetized fermi electron gas *Phys. Plasma-Ph 2830* **1** 1212
[14] Lindsay S M 2010 *Introduction to Nanoscience* (Oxford: Oxford University Press)
[15] Giazotto F *et al* 2007 Landau cooling in metal-semiconductor nanostructures *New J. Phys.* **9** 439
[16] Shalaev V M and Kawata S 2007 *Nano-Optics and Nano- Photonics* (Amsterdam: Elsevier)
[17] Landau L D and Lifshitz E M 1980 *Statistical Physics, Part 1* (Oxford: Pergamon)
[18] Hussain A, Stefan M and Brodin G 2014 Weakly relativistic quantum kinetic theory for electrostatic wave modes in magnetized plasmas *Phys. Plasmas* **21** 032104
[19] Brodin G and Zamanian J 2022 Quantum kinetic theory of plasmas *Reviews of Modern Plasma Physics* **6** 4

[20] Naseri H A, Zamanian J, Ekman R and Brodin G 2020 Kinetic theory for spin-1/2 particles in ultrastrong magnetic fields *Phys. Rev.* E **102** 043203

[21] Shu Lin Lixin Yang 2020 Chiral kinetic theory from Landau level basis *Phys. Rev.* D **101** 034006

[22] Hussain M S, Hussain A, Iqbal Z and Murtaza G 2018 Role of electron quantization on plasma shielding potentials *Phys. Plasmas* **25** 1121061

[23] Potekhin A Y, Chabrier G, Lai D, Ho W C G and van Adelsberg M 2006 Nonideal strongly magnetized plasmas of neutron stars and their electromagnetic radiation *Mathematical and General J. Phys. (A: Math. Gen.)* **39** 4453–8

[24] Rozina C, Maryam P and Tsintsadze N L 2021 Novel features of magnetization in weakly ionized neutron star *Phys. Scr.* **96** 015604

[25] Tsintsadze L N, Rozina C and Tsintsadze N L 2019 Solitary sound waves in weakly dispersive neutron stars *Phys. Plasmas* **26** 122103

[26] Shapiro S L and Teukolsky S A 1983 Black holes, white dwarfs, and neutron stars: the physics of compact objects (New York: WileyJ. Landstreet 1967) *Phys. Rev.* **153** 1372

[27] Kaspi V M and Beloborodov A M 2017 *Magnetars ARA&A* **55** 261

[28] Petroff E, Hessels J W T and Lorimer D R 2019 *Fast Radio Bursts A&AR* **27** 4

[29] Shi Y, Qin H and Fisch N J 2018 Laser-plasma interactions in magnetized environment *Phys. Plasmas* **25** 055706

[30] Blandford R D and Scharlemann E T 1976 On the scattering and absorption of electromagnetic radiation within pulsar magnetospheres *Mon. Not. R. ast. Soc.* **174** 9585

[31] Fedotov A B, Naumov A N, Silin V P, Uryupin S A, Zheltikov A M, Tarasevitch A P and von der Linde D 2000 Third-harmonic generation in a laser-pre-excited gas: the role of excited-state neutrals *Phys. Lett.* A **271** 407

[32] Sarkisov G S, Bychenkov V Y, Novikov V N, Tikhonchuk V T, Maksimchuk A, Chen S Y, Wagner R, Mourou G and Umstadter D 1999 Self-focusing, channel formation, and high-energy ion generation in interaction of an intense short laser pulse with a He jet *Phys. Rev.* E **59** 7042

[33] Walia K and Singh A 2014 Comparison of two theories during self-focusing of Gaussian laser beam in thermal conduction-loss predominant plasmas *Optik* **125** 989

[34] Singh A and Walia K 2010 Relativistic self-focusing and self-channeling of Gaussian laser beam in plasma *Appl. Phys. B Lasers Opt.* **101** 617

[35] Tyagi Y, Tripathi D and Walia K 2017 Laser second harmonic generation in a magnetoplasma assisted by an electrostatic wave *Phys. Plasmas* **24** 043104

[36] Tyagi Y, Tripathi D, Walia K and Garg D 2018 Ion acoustic wave assisted laser beat wave terahertz generation in a plasma channel *Phys. Plasmas* **25** 0431188

[37] Bingham R, Mendonça J T and Shukla P K 2004 Plasma based charged-particle accelerators *Plasma Phys. Controlled Fusion* **46** 1

[38] Mahmoudian A, Scales W A, Bernhardt P A, Isham B, Kendall E, Briczinski S J, Fuentes N E B and Vega-Cancel O 2014 Electrongyroharmonic effects on ionospheric stimulated Brillouin scatter *Geophys. Res. Lett.* **41** 5710–6

[39] Obenschain S P *et al* 1989 Reduction of raman scattering in a plasma to convective levels using induced spatial incoherence *Phys. Rev. Lett.* **62** 768

[40] Rousseaux C *et al* 1995 Experimental validation of the linear theory of stimulated raman scattering driven by a 500-fs laser pulse in a preformed underdense plasma *Phys. Rev. Lett.* **74** 4655

[41] Preussler S and Schneider T 2016 Stimulated Brillouin scattering gain bandwidth reduction and applications in microwave photonics and optical signal processing *Opt. Eng.* **55** 031110

[42] Froula D H *et al* 2012 Increasing hydrodynamic efficiency by reducing cross-beam energy transfer in direct-drive- implosion experiments *Phys. Rev. Lett.* **108** 125003

[43] Moody J *et al* 2012 Multistep redirection by cross-beam powertransfer of ultrahigh-power lasers in a plasma *Nat. Phys.* **8** 344

[44] Marozas J A *et al* 2018 First observation of cross-beam energytransfer mitigation for direct-drive inertial confinement fusion implosions using wavelength detaining at the national ignition facility *Phys. Rev. Lett.* **120** 085001

[45] Zheleznyakov V V 1996 *Radiation in Astrophysical Plasmas* (Springer, Dordrecht: Kluwer Academic Publishers) (https://doi.org/10.1007/978-94-009-0201-5)

[46] Bawa'aneh M S 2003 Stimulated brillouin backscattering in magnetized plasmas contrib *Plasma Phys.* **43** 447

[47] Tajima T and Dawson J M 1979 Laser electron accelerator *Phys. Rev. Lett.* **43** 267

[48] Umstadter D, Kim J K and Dodd E 1996 Laser injection of ultrashort electron pulses into wakefield plasma waves *Phys. Rev. Lett.* **76** 2073

[49] Umstadter D and Norris T B 1997 Nonlinear optics with relativistic electrons *IEEE J. Quantum Electon.* **33** 1877

[50] Maximov A V, Oppitz R M, Rozmus W and Tikhonchuk V T 2000 Nonlinear stimulated Brillouin scattering in inhomogeneous plasmas *Phys. Plasmas* **7** 4227

[51] Shukla P K and Stenflo L 2006 Stimulated scattering instabilities of electromagnetic waves in an ultracold quantum plasma *Phys. Plasmas* **13** 044505

[52] Rozina C, Ali S, Maryam N and Tsintsadze N L 2018 Raman and Brillouin scattering instabilities of transverse electromagnetic waves in degenerate electron-ion plasmas *Phys. Plasmas* **25** 093302

[53] Yin L, Albright B, Rose H, Montgomery D, Kline J, Kirkwood R, Michel P, Bowers K and Bergen B 2013 Selforganized coherent bursts of stimulated Raman scatteringand speckle interaction in multi-speckled laser beams *Phys.Plasmas* **20** 012702

[54] Paknezhad A 2016 Effect of DC-magnetic field on the growth rate of Raman backscattering of X-mode laser in magnetizedcollisional plasma Laser Part *Beams* **34** 80

[55] Winjum B, Tsung F and Mori W 2018 Mitigation of stimulated Raman scattering in the kinetic regime by external magneticfields *Phys. Rev.* E **98** 043208

[56] Shi Y, Qin H and Fisch N J 2017 Laser-pulse compressionusing magnetized plasmas *Phys. Rev.* E **95** 023211

[57] Jia Q, Shi Y, Qin H and Fisch N J 2017 Kinetic simulations of laser parametric amplification in magnetized plasmas *Phys. Plasmas* **24** 093103

[58] Matthew R E, Shi Y, Mikhailova J M and Nathaniel J F 2019 Laser amplification in strongly magnetized plasma *Phys. Rev. Lett.* **123** 025001

[59] Berestetskii B V, Lifshitz E M and Pitaevskii L P 1999 *Quantum Electrodynamics* (Oxford: Butterworth—Heinemann)

[60] Landau L D and Lifshitz E M 1989 *Statistical Physics Part 1* (Oxford: Pergamon) 175

[61] Tsintsadze N L and Tsintsadze L N 2015 Some aspects of statistical thermodynamics of a magnetized fermi gas *Phys. Plasma. ph* arXiv: 1.510.0878v1

[62] Tsintsadze L N, Peradze G M and Tsintsadze N L 2020 Landau-Kelly representation of statistical thermodynamics of a quantum plasma and electron emission from metals *J. Plasma Phys.* **86** 905860309

[63] Tsintsadze N L, Rozina C, Ruby R and Tsintsadze L N 2018 Jeans anisotropic instability *Phys. Plasmas* **25** 073705
[64] Rozina C, Tsintsadze N L and Tsintsadze L N 2020 Magnetic field quantization in pulsars *J. Plasma Phys.* **86** 905860211
[65] Von Ortenberg M 2006 Physics of semiconductors in high magnetic fields *J. Phys. Conf. Ser.* **51** 371–8
[66] Zhang H T and Zhang X 2022 Strong magnets with ordered structures *Matter. Res. Lett.* **10** 1–5
[67] Manfredi G, Hervieux P A and Hurst J 2021 Fluid descriptions of quantum plasmas *Reviews of Modern Plasma Physics* **5** 1–38
[68] Safder A, Mushtaq A, Esmaeli A, Akram M and Sadiq N 2021 MHD Waves with Landau diamagnetic pressure and Pauli paramagnetism in degenerate plasmas *Phys. Scr.* **96** 015603
[69] Misra A P and Chatterjee D 2018 Stimulated scattering instability in a relativistic plasma *Phys.plasm-ph* **25** 6 arXiv:1802.09260
[70] Kazuki M *et al* 2017 Magnetohydrodynamics of laser-produced high-energy-density plasma in a strong external magnetic field *Phys. Rev.* E **95** 053204
[71] Stenflo L 2004 Comments on stimulated electromagnetic emissions in the ionospheric plasma *Phys. Scr.* T **107** 262