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Stopping power of two-dimensional spin quantum electron gases

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ABSTRACT

Quantum effects can contribute significantly to the electronic stopping powers in the interactions between the fast moving beams and the degenerate electron gases. From the Pauli equation, the spin quantum hydrodynamic (SQHD) model is derived and used to calculate the stopping power and the induced electron density for protons moving above a two-dimensional (2D) electron gas with considering spin effect under an external in-plane magnetic field. In our calculation, the stopping power is not only modulated by the spin direction, but also varied with the strength of the spin effect. It is demonstrated that the spin effect can obviously enhance or reduce the stopping power of a 2D electron gas within a laboratory magnetic field condition (several tens of Tesla), thus a negative stopping power appears at some specific proton velocity, which implies the protons drain energy from the Pauli gas, showing another significant example of the low-dimensional physics.

1. Introduction

High energy (from few hundreds of keV up to GeV) intense ion beams can be used to generate high energy density matter when interacting with a solid target, which have been of long research interests in high energy density physics (HEDP) [1–4], inertial confinement fusion [5,6] and astrophysics [7]. High energy ions moving near a solid surface may lose their energy mainly due to the interaction with the electrons, thus the so-called stopping power of electron gases is of special interest.

Since the pioneer works by Bohr [8,9] with classical treatment, and with quantum mechanical approach by Bethe [10] and Bloch [11], stopping power has been the subject of extensive investigation [12–31]. The random-phase approximation (RPA) dielectric theory [12,13] and binary collision approach [19], have become two of the most used methods to calculate the stopping power. However, the dielectric function and binary collision approaches to stopping power of projectiles in plasmas are only valid in the regimes where the plasma is close to ideal, and the coupling between the charged particle and the plasma is weak [18]. Horing [13] investigated the stopping of a swift particle moving parallel to a 2D surface plasma with fixed distance and velocity, in the framework of the RPA description. Besides, Lindhard et al. [17] calculated the stopping power and the corresponding straggling for ions of arbitrary charge number and any relativistic velocity, and showed some important discrepancies of their results with the first-order quantum perturbation results. The stopping power for slow protons and antiprotons moving in 2D electron gases (2DEGs) was consistently calculated within the framework of quantum scattering theory [14]. A density-functional theory [21] was used to study the nonlinear screening and stopping properties of a 2D electron gas (2DEG), in which an external static point charge was considered. In recent works, one or two-fluid hydrodynamic model has been proven to be an effective method to study the interaction processes as well as the stopping power, which has been a major method in this area [22,23,32,27]. In addition, particle-in-cell (PIC) [25] and Monte-Carlo (MC) [20], were also adopted to study the stopping power in the interaction process between ions and plasmas. Lately, the molecular dynamics model was employed to study the electronic stopping power for protons and helium ions [29]. The stopping power for heavy ions in a thin silicon nitride and in thin polypropylene foils were measured experimentally by means of an indirect transmission method using a half-covered PIPS detector [30]. Again, the electronic energy loss of hydrogen ions was investigated experimentally by using Time-Of-Flight Medium-Energy Ion Scattering (TOF-MEIS) method [31].

Despite the large number of studies performed on the stopping power in plasmas, some of the contributing factors of electronic stopping powers are not included yet. For some cases, quantum

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effects can contribute significantly to the electronic stopping powers, especially for the cases when the de Broglie wavelength of the charge carriers is frequently comparable to the dimension of the system. In these cases, the electron gas can be partially degenerate, often referred as fermi gas, is in the Fermi–Dirac distribution instead of in the Maxwellian distribution as in classical gases. The quantum hydrodynamic model (QHD) [33,34], a self-consistent approach and a useful tool for describing the dynamics of quantum plasmas, by solving the nonlinear Schrödinger-Poisson or the Wigner-Poisson kinetic models, has been applied to investigate the stopping power of electron gases at any degeneracy [24,26]. However, in these works, only quantum diffraction and quantum statistical effects are included. It is expected that new features could appear with considering further quantum effects in describing quantum plasmas, especially the spin effects.

Recently, the coupling of spin to quantum plasmons [35–40] has attracted interest. It is possible to study such a system with spin quantum hydrodynamic model (SQHD), which is developed recently [35] by Marklund et al. They have shown an obvious spin quantum effects [35] in dispersion relation and the linear response of the quantum plasmas. With similar SQHD model, Brodin et al. [36] has given a number of different models for treating spin and magnetization effects in plasmas, wake fields were generated by whistlers in spin quantum magnetoplasmas [37], Asenjo et al. [38] investigated relativistic corrections to the Pauli Hamiltonian in the context of a scalar kinetic theory for spin-1/2 quantum plasmas, Mahajan et al. [39] investigated vortical Dynamics of spin quantum plasmas with Helicity conservation, and a spin-gradient-driven light amplification achieved in a quantum plasma [40]. In particular, it has been reported that the spin-effects can become important if magnetic field in the quantum plasma was larger than 10^8 T [35,37], such a large magnetic field can exist in the vicinity of pulsars and magnetars. However, the spin-effect on the stopping power of quantum plasmas has not been examined so far.

In above works, it is generally believed that spin effects in quantum plasmas can never be observed in the experimental conditions, since the strongest magnetic field achieved in labs is no larger than 1000 T. In this work, we study the stopping power of a completely degenerate 2DEG with spin effect for a charged particle moving parallel to the surface of the 2DEG, with the SQHD model. For a applied magnetic field in a laboratory condition (several tens of T), the spin effect obviously enhances or reduces the stopping power dependant on spin-up or -down and negative stopping power is obtained, showing another significant example of the low-dimensional phenomenon. The outline of the paper is as follows. In Section 2, the SQHD model is derived from Pauli equation. In Section 3, general expressions for the induced potential, the perturbed electron density and the stopping power with spin effect are derived on the basis of SQHD equations, coupled with the Poissons equation. In Section 4 we show numerical results of the stopping power and the perturbed electron density, and present the spin effect on them. Finally, a short summary is given in Section 5. Gauss units will be adopted throughout the paper except in specific definitions.

2. Spin quantum hydrodynamic model

By introducing the non-relativistic evolution of spin electrons, as described by the two-component spinor $\psi = \sqrt{n_e}\exp(iS/\hbar)\varphi$ with the relation $m_e\mathbf{u}_e = \nabla S + e\mathbf{A}/c$, it is possible to derive non-relativistic quantum continuity and momentum equations for the density n_e and velocity $\mathbf{u_e}$, from the Pauli equation

$$i\hbar\frac{\partial\psi}{\partial t} = \frac{1}{2m_e}\left(-i\hbar\nabla - \frac{e}{c}\mathbf{A}\right)^2\psi + \mu_B\mathbf{B}\cdot\sigma\psi - e\phi\psi + w_e\psi. \quad (1)$$

Here m_e is the electron mass, $\mathbf{A}$ is the vector potential, e is the magnitude of the electron charge, $\mu_B = e\hbar/2m_ec$ is the electron magnetic moment, ϕ is the electrostatic potential, $\sigma = (\sigma_x, \sigma_y, \sigma_z)$ are the Pauli spin matrices, and $w_e = \int_n \frac{dn'}{n'}\frac{dP_en'}{dn'}$ is the pressure-related effective potential. We take the z direction as the spin-quantization (polarization) axis with φ satisfying $\varphi^+\varphi = 1$. Thus, in an external magnetic field $\mathbf{B} = B_z(z)\hat{z}$, since the spin vector $S_z = \hbar/2\sigma_z$ is a conserved quantity in the Hamiltonian described above, which means $\varphi = 1/\sqrt{2}(1,0)$ for spin-up and $\varphi = 1/\sqrt{2}(0,1)$ for spin-down, the Pauli equation can be written for spin-up and spin-down electrons,

$$\left[i\hbar\frac{\partial}{\partial t} + \frac{\hbar^2}{2m_e}\nabla^2 - \frac{e^2A^2}{2m_ec^2} - \frac{i\hbar}{2m_e}\frac{e}{c}(\nabla\cdot\mathbf{A} + \mathbf{A}\cdot\nabla) + e\phi \mp \mu_B B_z - w_e\right]\sqrt{n_e}\exp(iS/\hbar) = 0, \quad (2)$$

where "−" represents spin-up and "+" represents spin-down in the term $\mp\mu_B B_z$. Separating Eq. (2) into their real and imaginary parts, we indeed obtain the continuity equation,

$$\frac{\partial n_e}{\partial t} + \nabla\cdot(n_e\mathbf{u}_e) = 0, \quad (3)$$

and the momentum-balance equation

$$\frac{\partial}{\partial t}\nabla S + \frac{1}{2m_e}\nabla(\nabla S)^2 = e\nabla\phi \mp \mu_B\nabla B_z - \nabla w_e + \frac{\hbar^2}{2m_e}\nabla\left(\frac{1}{\sqrt{n_e}}\nabla^2\sqrt{n_e}\right), \quad (4)$$

with "∓" representing spin-up and spin-down, respectively in the term $\mp\mu_B\nabla B_z$. Here we have used the Coulomb gauge $\nabla\cdot\mathbf{A} = 0$. By using $\nabla S = m_e\mathbf{u}_e - e\mathbf{A}/c$ and $\frac{1}{2m_e}\nabla(\nabla S)^2 = m_e\mathbf{u_e}\cdot\nabla\mathbf{u_e} + e/c[\mathbf{u_e}\times\mathbf{B}]$, the Eq. (4) can be simplified as

$$m_e\left(\frac{\partial\mathbf{u}_e}{\partial t} + \mathbf{u}_e\cdot\nabla\mathbf{u}_e\right) = e\left(\nabla\Phi - \frac{\mathbf{u}_e\times\mathbf{B}}{c}\right) \mp \mu_B\nabla B_z - \nabla w_e + \frac{\hbar^2}{2m_e}\nabla\left(\frac{1}{\sqrt{n_e}}\nabla^2\sqrt{n_e}\right) - \gamma m_e\mathbf{u_e}. \quad (5)$$

Here we add the collision term $-\gamma m_e\mathbf{u_e}$ with the frequency γ. On the right side of Eq. (5), the first term is the electromagnetic force, the second term is induced by the spin quantum effect (Zeeman energy), the third term is denoted as the quantum statistical pressure force with $w_e = \hbar^2(3\pi^2n_e)^{2/3}/2m_e$, the forth term is quantum Bohm potential, and the last therm is collision force. Here the quantum statistical pressure and the Bohm potential terms are the same as in a non-spin QHD equations [34].

3. Application for a two-dimensional spin quantum electron gas

We consider a two-dimensional spin quantum electron gas (2DSQEG) with spin quantum effect located in the plane (z, x) $(y = 0)$, which is composed of free electrons and motionless ions with an equilibrium density $n_{i0} = n_{e0} = n_0$ in a full degenerate case, and the vacuum in the region $y > 0$ of a cartesian coordinate system with $\mathbf{R} = \{x, y, z\}$. A particle of charge Z_1e moves parallel to the 2D plane (z, x) along the z axis with a constant velocity $\mathbf{v} = v\mathbf{e}_z$ and density $n_{\text{ext}} = \delta(\mathbf{r} - \mathbf{v}t)\delta(y - y_0)$, where $\mathbf{r} = r(z, x)$ and y_0 is the distance from the plane. Therefore, the homogeneous electron gas is perturbed by the charged particle and can be regarded as a charged fluid with velocity $\mathbf{u}_e(\mathbf{r}, t)$ and density $n_e(\mathbf{r}, t)$. Moreover, in order to examine the spin effect on the stopping power of the 2DSQEG, an external magnetic field $\mathbf{B} = \{0, 0, B_z(z, t)\}$ is applied to the electron gas with zero perpendicular-plane component but nonzero in-plane component $B_z(z, t) = B_0\exp[i(k_0z - \omega_0t)]$. Because only by considering the spin effect the