Physics Letters A 379 (2015) 2777–2782

Contents lists available at ScienceDirect

Physics Letters A

www.elsevier.com/locate/pla

Spin current evolution in the separated spin-up and spin-down quantum hydrodynamics

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ARTICLE INFO

Article history:
Received 4 March 2015
Received in revised form 3 August 2015
Accepted 13 August 2015
Available online 18 August 2015
Communicated by A. Eisfeld

Keywords:
Spin current
Quantum hydrodynamics
Sound wave
Spin-up and spin-down systems

ABSTRACT

We have developed a method of quantum hydrodynamics (QHD) that describes particles with spin-up and with spin-down in separate. We have derived the equation of the spin current evolution as a part of the set of the quantum hydrodynamics equations that treat particles with different projection of spin on the preferable direction as two different species. We have studied orthogonal propagation of waves in the external magnetic field and determined the contribution of quantum corrections due to the Bohm potential and to magnetization energy of particles with different projections of spin in the spin-current wave dispersion. We have analyzed the limits of weak and strong magnetic fields.

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1. Introduction

Spin current is a very important concept of physics. For instance it is useful in spintronics and in the physics of quantum plasma of spinning particles. Spin current generation, detection and manipulation are of the particular interest for magnetoelectronic devices research. The establishment of methods for injecting of spin currents and manipulating spin information has been reported in Refs. [1–8]. The demonstration of spin current injection and detection at room temperature using the geometries and interfaces between ferromagnetic electrodes in combination with a tunnel barrier and nonmagnetic metal was implemented by Jadema et al. [3–5]. The direct electronic measurement of the Hall-effect-induced spin current in a lateral geometry has been shown in Ref. [1] and the induced voltage in the conductor that results from the conversion of the injected spin current into charge imbalance owing to the spin–orbit coupling was measured.

The magnetic domain wall displacement by spin-polarized current had been confirmed using the magnetic wires [6,7]. The real-space observation of current-driven magnetic domain wall displacement using a well-defined single domain wall in a micro-fabricated magnetic wire was demonstrated in Ref. [8]. The nature of the influence of spin diffusion in current-induced domain wall motion was studied in theory in Ref. [9]. The effect of the conduction electrons' spins on spatial and temporal magnetization dynamics of a ferromagnetic wire was recently subjected to theoretical research [10,11] in the time-dependent semiclassical transport theory.

Spin-polarized currents are studied using the phenomenon of spin transfer torque in which the angular momentum of a spin polarized electrical current entering a ferromagnet is transferred to the magnetization [12–14] and the spin pumping phenomenon that is the transfer of the spin angular momentum from magnetization precession motion to conduction-electron spin [15]. Spin-polarized currents are used in spin-diode structures [16,17] and in observation of the spin Peltier effect [18,19]. It was shown that the spin Peltier effect requires independent heat transport in spin-up and spin-down channels [20]. The collective motion of spin – spin wave – can carry non-equilibrium spin currents and transfer a signal in some magnetic insulators [21] and it has been shown that a spin-wave spin current may persist at much greater distances.

The interests and publications of research in spin dynamics and transports till increased. There are many theoretical publications that propose new definitions of spin current [22–24], in particular, in the presence of spin–orbit interaction [25]. The definition of the spin-current and the equation of the spin-current evolution had been derived earlier [26]. The spin current equation derived from the many-particle microscopic Schrodinger equation was used to study the dispersion of collective excitations in three dimensional samples of magnetized dielectrics. It had been shown that the dynamics of spin current leads to formation of a new type of collective excitations in magnetized dielectrics, which were called spin-current waves. The satisfactory description of spin transport in solids was presented in Refs. [27–29]. The phenomenological spin continuity equation that describes spin accumulation in solids

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http://dx.doi.org/10.1016/j.physleta.2015.08.013
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and contains novel expression for the spin current was presented in Ref. [28].

The properties of quantum plasmas had been studied by several authors [30–34]. The set of quantum hydrodynamics equations for charged and neutral spinning particle using the Pauli equation had been performed in Refs. of T. Takabayasi and P. Holland [35–39]. In Ref. [35] the author derived a set of hydrodynamic equations for a single spinning particle using the vector representation of a spinning particle. This paper is however based upon a different formalism. We consider spin-up and spin-down particles as two different species. We present our derivation of equations for the spin current evolution, which are a part of the set of QHD equations that describe in separate the evolution of spin-up and spin-down particles moving in an external magnetic field. Corresponding spin current evolution equations were directly derived from the Pauli equation. This derivation can be performed in context of quantum hydrodynamics method which was developed in Refs. [40–43].

On the other hand systems of spin-up and spin-down particles are in the focus of resent studies. A quantum hydrodynamics model of charged spin-1/2 particles was developed in Refs. [44–46]. The set of equations, which separately describes spin-up electrons and spin-down electrons, was derived: the continuity equation (particle number evolution equation), the Euler equation (momentum balance equation) and the Bloch equation (magnetic moment balance equation). Application of the separated spin evolution quantum hydrodynamics to two-dimensional electron gas in plane samples and nanotubes placed in external magnetic fields have revealed the spin-electron acoustic wave in the electron gas [45]. The dispersion equations for the longitudinal waves were found in Ref. [44] and the limits of weak and strong magnetic fields were considered. The authors have studied propagation of waves parallel to external magnetic field and have found contribution of magnetic field in the Langmuir wave dispersion via difference of occupation of spin-up and spin-down states. In this paper we present further application of separated spin evolution QHD.

Longitudinal and transverse dispersion relations including spin and exchange contributions had been derived for electromagnetic waves in a fully ionized plasma in Ref. [47]. The nonrelativistic Pauli description of the electrons had been used. It had been showed that the dispersion relation for longitudinal modes is unaffected by spin. The dispersion properties of plasma in an uniform magnetic field had been investigated in Ref. [48] using a kinetic model and the Wigner function had been shown to satisfy the Boltzmann–Vlasov equation in the long-wavelength approximation. The dispersion relations had been derived for longitudinal and transverse wave propagation.

The QHD model contains equations for evolution of the spin density projections, but does not contain the spin current evolution equations. The spin-current appears in the equations for evolution of the spin density projections and gives contribution in the force field in the equation of motion. Thus it is important to have the equations of spin-current dynamical evolution. Separated spin evolution QHD and new spin-current dynamical evolution equation show itself as an usefultool for research of spin transport in magnetic nanostructures. Using the developed model we have analyzed the contribution of the spin polarization to the spin-current wave dispersion. We apply the developed model to the magnetized dielectrics research.

2. Governing equations

In Ref. [44] it was shown that the evolution of charged spin-1/2 particles with spin-up and with spin-down is governed by the equations for time evolution of the *concentration of particles* $n_\uparrow(\mathbf{r},t)$ *and* $n_\downarrow(\mathbf{r},t)$, which are proportional to the probability density

$$\partial_t n_\uparrow + \nabla(n_\uparrow \cdot \mathbf{v}_\uparrow) = \frac{\gamma}{\hbar}(B_y S_x - B_x S_y), \qquad \text{and}$$
$$\partial_t n_\downarrow + \nabla(n_\downarrow \cdot \mathbf{v}_\downarrow) = \frac{\gamma}{\hbar}(B_x S_y - B_y S_x), \tag{1}$$

and for time evolution of the particle *currents for each projection of spin*

$$mn_\uparrow(\partial_t + \mathbf{v}_\uparrow \cdot \nabla)\mathbf{v}_\uparrow + \nabla p_\uparrow - \frac{\hbar^2}{4m} n_\uparrow \nabla\left(\frac{\Delta n_\uparrow}{n_\uparrow} - \frac{(\nabla n_\uparrow)^2}{2n_\uparrow^2}\right)$$
$$= qn_\uparrow\left(\mathbf{E} + \frac{1}{c}\mathbf{v}_\uparrow \times \mathbf{B}\right) + \gamma n_\uparrow \nabla B_z + \frac{\gamma}{2}(S_x \nabla B_x + S_y \nabla B_y)$$
$$+ \frac{m\gamma}{\hbar}(\mathbf{J}^x B_y - \mathbf{J}^y B_x), \tag{2}$$

and

$$mn_\downarrow(\partial_t + \mathbf{v}_\downarrow \cdot \nabla)\mathbf{v}_\downarrow + \nabla p_\downarrow - \frac{\hbar^2}{4m} n_\downarrow \nabla\left(\frac{\Delta n_\downarrow}{n_\downarrow} - \frac{(\nabla n_\downarrow)^2}{2n_\downarrow^2}\right)$$
$$= qn_\downarrow\left(\mathbf{E} + \frac{1}{c}\mathbf{v}_\downarrow \times \mathbf{B}\right) - \gamma n_\downarrow \nabla B_z + \frac{\gamma}{2}(S_x \nabla B_x + S_y \nabla B_y)$$
$$+ \frac{m\gamma}{\hbar}(\mathbf{J}^y B_x - \mathbf{J}^x B_y), \tag{3}$$

where q stands for the charge of the particles, for electrons ($q = -e$), m is the mass of the particles, γ is the gyromagnetic ratio, for electrons $\gamma = -g|e|\hbar/2m_e c$ and $g \simeq 1.00116$ is the g-factor. In the equations (1)–(3) we have the following physical quantities: $n_{\uparrow,\downarrow}(\mathbf{r},t)$ are the concentrations of particles in the point $\mathbf{r}$ and $\mathbf{v}_{\uparrow,\downarrow}(\mathbf{r},t)$ are the velocity fields of particles baring spin-up (spin-down), S_h are the projections of the spin density vector and $p_{\uparrow,\downarrow}(\mathbf{r},t)$ are the thermal pressures. The second and third terms on the left-hand side of Euler equations (2) and (3) represent gradients of the thermal pressure and of the Bohm potential. The second and third terms on the right-hand side describe the effect of the z-projection, x- and y-projections of magnetic field on spin densities of particles and characterize the parts of force field which represents the influence of the magnetic field on magnetic moments. The last group of terms is related to nonconservation of particle number with different spin-projection. This nonconservation provides a mechanism for the change of the momentum density in the extra force fields [44].

The spin density evolution S_x and S_y is given by [44]

$$\partial_t S_x + \nabla \mathbf{J}_x = \frac{2\gamma}{\hbar}(B_z S_y - B_y(n_\uparrow - n_\downarrow)), \qquad \text{and}$$
$$\partial_t S_y + \nabla \mathbf{J}_y = \frac{2\gamma}{\hbar}(B_x(n_\uparrow - n_\downarrow) - B_z S_x), \tag{4}$$

where $\mathbf{J}_x$ and $\mathbf{J}_y$ are spin currents. The first and second terms at right sides of equations (4) represent the action of torque exerted by a magnetic field on a magnetic moments. The spin density projection on "z" direction presents the difference between concentrations of particles with different projection of spin $S_z = n_\uparrow - n_\downarrow$ and the spin-current $\mathbf{J}_z = \mathbf{j}_\uparrow - \mathbf{j}_\downarrow$ is the difference between the particle currents of particles with different projection of spin $\mathbf{j}_{\uparrow,\downarrow}$.

2.1. Spin current evolution

Next in this section we are going to represent the spin-current evolution equations for degenerate particles considering spin-up and spin-down states as two different species. We use the Pauli equation for a single particle in the external electromagnetic field [44] and self-consistent field approximation [43]. We start

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