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Spin-current resonances in a magnetically inhomogeneous 2D conducting system

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The high-frequency transport in a two-dimensional conducting ring having an inhomogeneous collinear magnetic structure has been considered in the hydrodynamic approximation. It is shown that the frequency dependence on the radial electric conductivity of the ring exhibits resonances corresponding to new hybrid oscillations in such systems. The oscillation frequencies are essentially dependent on the applied electromagnetic field and the spin state of the system.

1. Introduction

Spin accumulation in conducting nanosystems remains a problem of continuous keen interest [1]. Its dynamic aspect was investigated for the first time in [2]. In a conductor with inhomogeneous magnetic properties a nonequilibrium spin concentration generates forces acting on the spin components of the carriers and exciting coupled spin-current oscillations (we call them a "spin pendulum"). In this study we consider the possibility of spin-current resonances in a two-dimensional conducting ring in a nonquantizing magnetic field. As an example, the above effects are examined in a nondegenerate electron system on the liquid helium surface (*ESLH*) and in two-dimensional semiconducting heterostructures. Magnetic inhomogeneity of these systems can be induced in various ways, for example, by introducing nonequilibrium concentrations of magnetic impurities, applying spatially inhomogeneous magnetic fields or inhomogeneous electrostatic gate fields commonly used in experiments on heterostructures [3]. Experimental observation of resonances investigated in the article is the way to reveal of previously predicted by us [2] "spin pendulum" oscillations of the conductor spin system, and study effects associated with them.

For the experimental realization of the predicted effects, one can use materials which are widely used in experiments with 2D electronic conductors in heterostructures [4] based on GaAs and *ESLH*. The problem is only in the creation of the spatial inhomogeneity of the spin polarization conductor by methods suggested above.

Previously we investigated closely the transport and the spin-electric effect in the *ESLH* employing the quasi-equilibrium approximation [5], i.e., in external electromagnetic fields whose frequencies were low enough to permit the spin diffusion to form the equilibrium electron distribution under the influence of the forces of the inhomogeneous magnetic field acting on the spins. It was shown that within the range used the longitudinal and lateral electrical resistances in the magnetic field were determined not only by the momentum-loss scattering of electrons, but also by the electron–electron collisions generally dominant in the *ESLH* [6] and important in low-dimensional semiconducting structures [7]. This study is concerned with the transport properties of the mentioned inhomogeneous systems at relatively high frequencies of the external field. It is shown that new resonances can be formed involving the spin degree of freedom. The conditions of their observation have been studied.

2. Two-liquid hydrodynamics of conducting spin systems

The description of conducting systems possessing the spin degree of freedom in the two-liquid hydrodynamic approximation was substantiated in [2]. A similar approach was employed earlier in [8]. For simplicity, we consider a system with collinear magnetization. To put it differently, the system is an incoherent mixture of "spin-up" and "spin-down" states, i.e., two electron spin components. The hydrodynamic approximation is valid when the momentum–conservation collisions in the electron system (normal

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collisions) dominate over other possible ones [9]. We assume that the inequality $\nu_{ee} \gg \nu$ (ν_{ee} is the frequency of electron–electron collisions, ν is the frequency of electron collisions with possible structure imperfections) is obeyed and the mean free path is $l_{ee} \ll L$ and $\nu_{ee} \gg \omega$, where L and ω are the characteristic lengths and frequencies of the problem, respectively. This condition holds true in the *ESLH* [6] and heterostructures [10].

In the *ESLH* currents are generated in a noncontact way by applying an AC electric potential to the electrodes located near the *ESLH*. The same technique is applicable for low-dimensional heterostructures. In this case the polarized charges ρ_e induced by the electrodes in the electron system or the corresponding polarization currents related to the charges according to the continuity equation $div\,\boldsymbol{j}_e = -\partial\rho_e/\partial t$ can be taken as pre-assigned parameters.

According to [5], the following linearized system of hydrodynamic equations can be written down:

$$i\omega(\rho_{e\sigma} + \delta\rho_\sigma) + div\,\rho_\sigma \boldsymbol{u}_\sigma = -\nu_s \Pi^*(\mu_\sigma - \mu_{-\sigma}) \tag{1}$$

$$(i\omega + \nu)m\boldsymbol{u}_\sigma - e\frac{[\boldsymbol{u}_\sigma \boldsymbol{H}]}{c} + \nabla(\mu_\sigma + e\varphi) = -m\frac{\rho_{-\sigma}}{\rho}\nu_{ee}(\boldsymbol{u}_\sigma - \boldsymbol{u}_{-\sigma}) \tag{2}$$

$$\sum_\sigma \delta\rho_\sigma = 0 \tag{3}$$

$$\Pi^{*-1} = \sum_\sigma \Pi_\sigma^{-1} \tag{4}$$

This system is for a "good" conductor [5] in which the departure from electric neutrality is related only to the polarization charges providing in the first approximation a steady potential along the conductor; φ is the next approximation to the potential induced by the flowing current. We have $\delta\rho_{e\sigma} = 0$ when the current source is connected directly. It is convenient to choose the spin components of the polarization charge in the equilibrium form: $\rho_{e\sigma} = \Pi_\sigma \rho_e/\Pi$, $\Pi = \sum_\sigma \Pi_\sigma$ (however, the total density of the component $\rho_{e\sigma} + \delta\rho_\sigma$ can be far from equilibrium). In Eqs. (1)–(4) ω is the frequency of the applied electric field, $\delta\rho_\sigma$ is the non-equilibrium addition to the density of the electrons with the spin projections σ onto the chosen direction, ρ_σ is the equilibrium density which is assumed to be spatially inhomogeneous due to the applied nonuniform electric and magnetic fields and nonequilibrium concentrations of magnetic impurities; ν_s is the frequency of the spin-flip processes, $\delta\mu_\sigma$ is the nonequilibrium addition to the chemical potential of the spin component in the ESLH case when the momentum distribution of electrons can be considered classical; $\delta\mu_\sigma = T(\delta\rho_\sigma/\rho_\sigma)$, T is the temperature; Π_σ is the density of states of the spin component at the Fermi surface; $\boldsymbol{u}_\sigma = \boldsymbol{j}_\sigma/\rho_\sigma$ is the drift velocity, $\boldsymbol{H}$ is the magnetic field component perpendicular to the two-dimensional plane, ν is the frequency of momentum-loss collisions of electrons, ν_{ee} is the frequency of electron–electron collisions (see the description [11] of the processes of scattering in spin-polarized transport). It is found [5] that at relatively low frequencies the drift velocities of spin components can differ significantly even when the drift approximation is applicable.

At frequencies exceeding the inverse time of spin diffusion within the boundaries of the sample the rate variations in spin components are negligible. In this case it is convenient to multiply Eq. (2) by ρ_σ and sum it over σ:

$$(i\omega + \nu)m\boldsymbol{j} + \sum_\sigma \rho_\sigma \nabla\mu_\sigma + \rho e \nabla\varphi - \frac{e}{c}[\boldsymbol{jH}] = 0 \tag{5}$$

Here $\rho_0 = \sum_\sigma \rho_{0\sigma}$ is the total equilibrium charge density, $\boldsymbol{j} = \rho_0 \boldsymbol{u}$ is the total electron flow. On summation the right-hand side of Eq. (2) loses the term describing the mutual friction of the electron components.

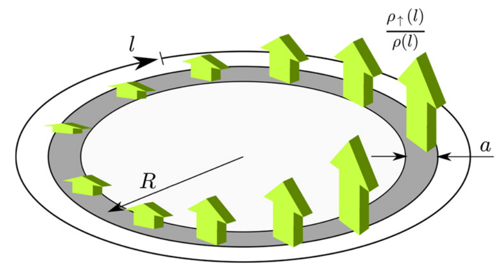

Fig. 1. Scheme of the proposed experiment: 2D magnetically inhomogeneous conducting ring with the width a and radius R. The annular geometry of the proposed experiment is fundamentally important for considered effect, because this allows current to flow in the direction perpendicular to the applied electric field direction.

3. Spin-current and combined spin–cyclotron resonances

Consider a two-dimensional conducting ring with the radius R and width a (see Fig. 1). The ring is connected, directly or in a noncontact way, to an AC current source along its outer and inner boundaries. Apart from the mentioned small parameters of the problem, we take into account the geometric small parameter $a \ll 2\pi R = L$ which normally corresponds to the experimental conditions on the ESLH. The properties of the conductor and the magnetic field are assumed to be homogeneous along the radial coordinate r.

Note that in the main approximation with respect to the geometric small parameter the polarization charge density $\rho_{e\sigma}$ can be taken as an odd function of the r-coordinate ($-a/2 < r < a/2$). Therefore, on averaging the sought-for values over r the term for polarization charges drops out of Eq. (1). Assuming equal drift velocities for the spin components (see above) we have $\boldsymbol{j}_\sigma = \rho_\sigma \boldsymbol{u} = \boldsymbol{j}\rho_\sigma/\rho$. Averaged Eq. (1) gives:

$$\delta\rho_\sigma = -(i\omega + \nu_s)^{-1} j_l \frac{d}{dl}\left(\frac{\rho_\sigma}{\rho}\right). \tag{6}$$

Here l is the coordinate along the ring. The equation takes into account the absence of a current flow through the sample boundaries on a noncontact connection. In the case of direct connection equation (6) is also valid if densities of the in- and out-currents at the same l are equal to each other. The latter may be provided by the homogeneity of the lead-in and the lead-out when the resistivity of the material of the contacting leads is much higher than that of the ring. j_l is the l-projection of the width-averaged total electron flow in the ring. It is l-independent by virtue of electric neutrality (result of σ-summed Eq. (1) and Eq. (3)). Henceforward the notation of averaging is omitted since we use only r-averaged quantities (except for Eq. (12)).

Averaging Eq. (5) over r we obtain in the r- and l-projections:

$$(i\omega + \nu)mj_r + \frac{e}{a}\rho\left[\varphi(a/2) - \varphi(-a/2)\right] + \frac{eH}{c}j_l = 0 \tag{7}$$

$$(i\omega + \nu)mj_l - \sum_\sigma \rho_\sigma \frac{d}{dl}\left[(i\omega + \nu_s)^{-1}\Pi_\sigma^{-1}\frac{dj_l(\rho_\sigma/\rho)}{dl}\right] + e\rho\frac{d\varphi}{dl} - \frac{eH}{c}j_r = 0 \tag{8}$$

According to Eqs. (4) and (6), μ_σ in Eqs. (7) and (8) is expressed in terms of the flows. The l-independent parameter j_l in the second term of Eq. (8) is kept under the derivative sign for using the equation in the next section. The term for the pressure difference at the ring edges is omitted from Eq. (7): according to estimation, this quantity is lower in parameter $a \ll L$ than the other contributions to the potential φ. After dividing both sides of Eq. (8) by ρ and performing integration over l within the boundaries of the ring we obtain: