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Spin back-flow effect in spin-polarized transport

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Abstract
The influence of electron correlations on spin-polarized transport is examined within a phenomenological approach based on the Landau theory of Fermi liquids. The inclusion of a spin-dependent interaction in the drift terms of the Boltzmann transport equation satisfied by the spin-dependent distribution function n_σ leads to an 'apparent' charge current that is different from the spin σ current associated with the quasiparticle momentum flow. This effect originates in the back-flow current of opposite spins and its magnitude is proportional to the Landau phenomenological parameter that describes the angular average of the opposite-spin interaction and with the relative drift velocity of the two spin species.

1. Introduction

The problem of spin-polarized transport in structures of reduced dimensionality has come under close scrutiny recently given its importance in the realization of spintronic devices [1]. The anticipated future applications aside, it also presents an area rich in interesting physics that can showcase dynamic many-body effects not present in equilibrium.

In the simplest description, that neglects all electron–electron interactions, spin transport involves the independent, simultaneous motion of opposite-spin electrons driven by an effective electric field. The direction of the spin, as up, σ, or down, $\bar{\sigma}$, is assumed to be fixed either by an external magnetic field or by some injection process. The long spin relaxation times ($\tau \sim 1$ ns in metals [2] and $\tau \sim 10$ ns in semiconductors [3]) allow a meaningful description of the transport process in terms of spin-dependent transport equations which are controlled by scattering times of the order of 10^{-3}–10^{-4} ns. This independent spin channel picture has been used to analyse the spin diffusion in semiconductors [4] and to predict various possible applications to spintronic devices [5].

The incorporation of the electron–electron interaction introduces a coupling between the spin channels, described in general terms as the apparition of a spin-$\bar{\sigma}$ current in the presence of a spin-σ current. One such occurrence is the spin-drag effect, where the coupling is realized by the momentum exchanged between electrons of opposite spins through inelastic Coulomb collisions, the net result being the slowing down of the fastest spin current. When the driving force of the current is removed, the two spin currents are equal and of opposite polarization and the effect disappears [6, 7]. The rate of momentum transfer between the two spin species determines the magnitude of the drag, defined as the proportionality coefficient of the time derivative of the spin-σ current with the relative drift velocity of the two spin species [6]

$$\frac{\mathrm{d}\vec{j}_\sigma}{\mathrm{d}t} = -\gamma(\vec{v}_\sigma - \vec{v}_{\bar{\sigma}}). \tag{1}$$

Formally, within a Boltzmann transport equation approach, this effect arises from the explicit inclusion of the opposite-spin electron–electron scattering in the collision integral. Recent calculations done within the random phase approximation [6, 7] show that the spin drag increases the overall resistivity of the system, the enhancement becoming more pronounced the lower the dimensionality. In three dimensions (3D) the spin transresistivity, proportional to the spin drag, has an appreciable magnitude, which increases at elevated temperatures to a fraction of the usual resistivity of metals [6]. The density and temperature dependence of the effect have been analysed in one [7], two [7] and three dimensions [6] for degenerate and non-degenerate electron populations.

In this paper, we point out a different source of dynamic spin coupling. In a phenomenological description, this effect is generated by the change in the local energy of a quasiparticle (QP) of spin σ when both σ and $\bar{\sigma}$ distribution functions are driven out of equilibrium by a spin-dependent perturbation. The incorporation of a spin-dependent interaction in the drift terms of the Boltzmann transport equation leads to a continuity equation for the spin-σ population that implies a spin-σ current different from the spin-σ current associated with the momentum transport. This difference is proportional to the relative drift velocity of the two spin species

$$\vec{j}_d = -\alpha(\vec{v}_\sigma - \vec{v}_{\bar{\sigma}}), \tag{2}$$

where α is determined by the angular average of the opposite-spin interaction.

The nature of this dynamic spin coupling phenomenon is made apparent in the Landau–Silin [8, 9] theory of charged Fermi liquids, a theoretical environment with a long history of successful descriptions of physical phenomena determined by the many-body interaction in both metals and semiconductors in two and three dimensions, such as spin waves, collective spin and charge excitations and back-flow phenomena [10–13]. In this case, the formalism enables a straightforward handling of the spin-dependent part of the QP–QP interaction expressed in terms of the Landau phenomenological parameters and the QP densities.

In the following, a set of coupled spin-dependent transport equations for the fully interacting QP distribution functions is derived. Based on them the continuity equation for the spin-σ QP is derived. This connects the time variation of the spin-σ density with the divergence of a current that involves both σ and $\bar{\sigma}$. Next, we compare the latter with the proper spin-σ current, calculated as the sum of momenta carried per unit mass multiplied by the perturbed distribution function. The two currents differ by an amount determined by the angular average of the opposite-spin interaction and the relative drift velocity.

2. The spin-dependent transport equation

The system of interest is an electron gas with n particles per unit volume in d dimensions ($d = 2, 3$) embedded in a positive background to assure charge neutrality. An *a priori* spin polarization is assumed, such that $n_\sigma \neq n_{\bar{\sigma}}$. The degree of spin polarization $\zeta = (n_\uparrow - n_\downarrow)/n$ is considered a parameter of the problem, whose magnitude varies continuously between -1 and 1.

The electron system is treated like a two-component Fermi liquid: the electrons of momentum $\vec{p}$ and spin σ occupy states inside two Fermi surfaces of radii $p_{F\sigma} = 2\sqrt{\pi}[\Gamma(\frac{d}{2}+1)n_\sigma]\hbar$. ($\Gamma$ is the Euler function). The elementary excitations of the system are QPs of energy $\epsilon_{\vec{p}\sigma}$ and distribution function $\delta n^0_{\vec{p}\sigma}$, a picture meaningful only in a shell of thickness $k_B T$ from the Fermi surface where the damping is negligible and one can define an equilibrium state for QPs. $\delta n^0_{\vec{p}\sigma}$ represents an infinitesimal departure from the equilibrium QP distribution, $n^0_{\vec{p}\sigma} = [1 + \mathrm{e}^{(\epsilon_{\vec{p}\sigma}-\mu_\sigma)}]^{-1}$. The chemical potential μ_σ is equal to the first variational derivative of the free energy in respect to the particle σ number, and thus spin dependent.

The interaction between two QP in states $(\vec{p}\sigma)$ and $(\vec{p'}\sigma')$ is represented by a symmetric function whose most general form is

$$f_{\vec{p}\sigma;\vec{p}'\sigma'} = f^s_{\vec{p}\vec{p}'} + \vec{\sigma}\cdot\vec{\sigma}' f^a_{\vec{p}\vec{p}'}. \tag{3}$$

Formally, $f_{\vec{p}\sigma;\vec{p}'\sigma'}$ represents the second variational derivative of the free energy of the system in respect to the particle numbers. In a system of charged particles, this is the screened Coulomb interaction, which acquires a spin-dependent component when short-range, spin-dependent effects like exchange and correlations are included [15]. The latter are attributed almost entirely to opposite spins, as same spins are kept apart on account of the exclusion principle.

The energy of a QP of momentum $\vec{p}$ and spin σ is determined by its interaction with all the other members of the system

$$\epsilon^0_{\vec{p}\sigma} = \tilde{\epsilon}^0_{\vec{p}} + \sum_{\vec{k}',\sigma'} f_{\vec{p}\sigma;\vec{p}'\sigma'}\delta n^0_{\vec{p}'\sigma'}, \tag{4}$$

where $\tilde{\epsilon}^0_{\vec{p}} = \vec{p}^2/2m$ is the bare particle energy, with m the band mass. Under the application of an external driving force, here an electric field $\vec{E}(\vec{r},t)$, the QP distribution function will be perturbed, assuming a new local value

$$n_{\vec{p}\sigma}(\vec{r},t) = n^0_{\vec{p}\sigma} + \delta n_{\vec{p}\sigma}(\vec{r},t). \tag{5}$$

Choosing only an electric field as the external perturbation allows an independent study of longitudinal spin transport, as no spin-flip effects occur. A treatment of spin diffusion under the application of an electromagnetic field is presented in [11] and [16].

In a linear response approximation, the deviation from equilibrium, $\delta n_{\vec{p}\sigma}(\vec{r},t)$, is considered infinitesimal. Consequently, the QP excitation energy $\epsilon_{\vec{p}\sigma}$ is modified to reflect the change in distribution function according to equation (4). The difference in respect to the equilibrium value is given by $\delta\epsilon_{\vec{p}\sigma}$

$$\delta\epsilon_{\vec{p}\sigma} = \sum_{\vec{p}'} f^{\sigma\sigma}_{\vec{p}\vec{p}'}\delta n_{\vec{p}'\sigma} + \sum_{\vec{p}'} f^{\sigma\bar{\sigma}}_{\vec{p}\vec{p}'}\delta n_{\vec{p}'\bar{\sigma}}, \tag{6}$$

where we introduced the usual Landau parameters $f^{\sigma\sigma}_{\vec{p}\vec{p}'} = f^a_{\vec{p}\vec{p}'} + f^s_{\vec{p}\vec{p}'}$ for the same-spin interaction and $f^{\sigma\bar{\sigma}}_{\vec{p}\vec{p}'} = f^s_{\vec{p}\vec{p}'} - f^a_{\vec{p}\vec{p}'}$ for the opposite-spin interaction.

The driven flow of the low-energy, non-interacting QPs in the phase space can be described by a transport equation. For spin-σ electrons, the Landau–Silin equation is written as

$$\frac{\partial n_{\vec{p}\sigma}}{\partial t} + \nabla_{\vec{p}}\epsilon_{\vec{p}\sigma}\nabla_{\vec{r}}n_{\vec{p}\sigma} - \nabla_{\vec{p}}n_{\vec{p}\sigma}\nabla_{\vec{r}}\epsilon_{\vec{p}\sigma} = \left(\frac{\partial n_{\vec{p}\sigma}}{\partial t}\right)_{coll.}. \tag{7}$$

(The time and position dependence of all quantities are understood, even if not explicitly declared.) Its linearized expression with respect to the modified particle distribution function and energy is readily obtained to be

$$\frac{\partial n_{\vec{p}\sigma}}{\partial t} + \nabla_{\vec{p}}\epsilon^0_{\vec{p}\sigma}\nabla_{\vec{r}}\delta n_{\vec{p}\sigma} + \nabla_{\vec{p}}\delta\epsilon_{\vec{p}\sigma}\nabla_{\vec{r}}n^0_{\vec{p}\sigma} - \nabla_{\vec{p}}n^0_{\vec{p}\sigma}\nabla_{\vec{r}}\delta\epsilon_{\vec{p}\sigma} - \nabla_{\vec{p}}\delta n_{\vec{p}\sigma}\nabla_{\vec{r}}\epsilon^0_{\vec{p}\sigma} = \left(\frac{\partial n_{\vec{p}\sigma}}{\partial t}\right)_{coll.}. \tag{8}$$

The equilibrium function derivatives are readily identified:

$$\nabla_{\vec{p}}\epsilon^0_{\vec{p}\sigma} = \vec{v}_{\vec{p}\sigma} \tag{9}$$

is the group velocity of the QP, while

$$\nabla_{\vec{r}}\epsilon^0_{\vec{p}\sigma} = e\vec{E} \tag{10}$$

is the external force on the system determined by the applied electric field $\vec{E}$. The derivatives of the equilibrium distribution function are obtained immediately, $\nabla_{\vec{p}} n^0_{\vec{p}\sigma} = (\mathrm{d}n^0_{\vec{p}\sigma}/\mathrm{d}\epsilon^0_{\vec{p}\sigma})\vec{v}_{\vec{p}\sigma}$ and $\nabla_{\vec{r}} n^0_{\vec{p}\sigma} = (-\frac{\mathrm{d}n^0_{\vec{p}\sigma}}{\mathrm{d}\epsilon^0_{\vec{p}\sigma}})\nabla_{\vec{r}}\mu_\sigma$. With these values, equation (8) becomes

$$\frac{\partial n_{\vec{p}\sigma}}{\partial t} + e\vec{v}_{\vec{p}\sigma}\cdot\vec{E}_\sigma\left(-\frac{\mathrm{d}n^0_{\vec{p}\sigma}}{\mathrm{d}\epsilon^0_{\vec{p}\sigma}}\right) + \vec{v}_{\vec{p}\sigma}\cdot\nabla_{\vec{r}}\left[\delta n_{\vec{p}\sigma} + \left(-\frac{\mathrm{d}n^0_{\vec{p}\sigma}}{\mathrm{d}\epsilon^0_{\vec{p}\sigma}}\right)\sum_{\vec{p}'} f^{\sigma\sigma}_{\vec{p}\vec{p}'}\delta n_{\vec{p}'\sigma} + \left(-\frac{\mathrm{d}n^0_{\vec{p}\sigma}}{\mathrm{d}\epsilon^0_{\vec{p}\sigma}}\right)\sum_{\vec{p}'} f^{\sigma\bar{\sigma}}_{\vec{p}\vec{p}'}\delta n_{\vec{p}'\bar{\sigma}}\right] = \left(\frac{\partial n_{\vec{p}\sigma}}{\partial t}\right)_{coll.}, \tag{11}$$

where $\vec{E}_\sigma = e[\vec{E} + (1/e)\nabla_{\vec{r}}\mu_\sigma]$ is the spin-dependent effective driving field of the current. In this form, equation (11) is equivalent to a diagonal element of the 2×2 matrix transport equation obtained in [11].

The collision term of the transport equation $(\partial n_{\vec{p}\sigma}/\partial t)_{coll.}$ can be written as a sum of different contributions arising from spin-flip and non-spin-flip impurity collisions and from the Coulomb interaction. The latter term describes the exchange of momentum between electrons of opposite spins, leading to a spin-drag current as described in [6] and it will not be considered here. Among the impurity scattering processes, the non-spin-flip ones are dominant and they are the limiting factor of the spin-σ current. Under these circumstances, a solution to the transport equation can be written in the relaxation time approximation as

$$\delta n_{\vec{p}\sigma} = -e\tau\vec{v}_{\vec{p}\sigma}\cdot\vec{E}_\sigma\left(-\frac{\mathrm{d}n^0_{\vec{p}\sigma}}{\mathrm{d}\epsilon^0_{\vec{p}\sigma}}\right), \tag{12}$$

where τ is the energy-independent momentum relaxation time, which determines the electron mobility.

The continuity equation for the charge carried by the spin-σ electrons is obtained by summing over the momentum $\vec{k}$ leading to

$$\frac{\partial(-en_\sigma)}{\partial t} + \nabla_{\vec{r}}\vec{j}'_\sigma = 0, \tag{13}$$

where the current $\vec{j}'_\sigma$ is defined by

$$\vec{j}' = -e\sum_{\vec{p}}\vec{v}_{\vec{p}\sigma}\left[\delta n_{\vec{p}\sigma} + \left(-\frac{\mathrm{d}n^0_{\vec{p}\sigma}}{\mathrm{d}\epsilon^0_{\vec{p}\sigma}}\right)\sum_{\vec{p}'} f^{\sigma\sigma}_{\vec{p}\vec{p}'}\delta n_{\vec{p}'\sigma} + \left(-\frac{\mathrm{d}n^0_{\vec{p}\bar{\sigma}}}{\mathrm{d}\epsilon^0_{\vec{p}\bar{\sigma}}}\right)\sum_{\vec{p}'} f^{\sigma\bar{\sigma}}_{\vec{p}\vec{p}'}\delta n_{\vec{p}'\bar{\sigma}}\right]. \tag{14}$$

The presence of a spin-dependent QP interaction makes premature the identification of $\vec{j}'_\sigma$ with the spin-σ current. We expand on this point below.

3. The momentum and the group velocity

In the Landau theory of Fermi liquids, the microscopic origin of the group velocity, equation (9), is revealed by considering equation (4)

$$\vec{v}_{\vec{p}\sigma} = \frac{\hbar\vec{p}}{m} + \sum_{\vec{p}'}\nabla_{\vec{p}} f^{\sigma\sigma}_{\vec{p}\vec{p}'}\delta n_{\vec{p}'\sigma} + \sum_{\vec{p}'}\nabla_{\vec{p}} f^{\sigma\bar{\sigma}}_{\vec{p}\vec{p}'}\delta n_{\vec{p}'\bar{\sigma}}. \tag{15}$$

Since both $f^{\sigma\sigma}_{\vec{p}\vec{p}'}$ and $f^{\sigma\bar{\sigma}}_{\vec{p}\vec{p}'}$ depend only on $|\vec{p}-\vec{p}'|$, $\nabla_{\vec{p}}(f^{\sigma\sigma}_{\vec{p}\vec{p}'}, f^{\sigma\bar{\sigma}}_{\vec{p}\vec{p}'}) = -\nabla_{\vec{p}'}(f^{\sigma\sigma}_{\vec{p}\vec{p}'}, f^{\sigma\bar{\sigma}}_{\vec{p}\vec{p}'})$. An integration by parts under the summation sign, allows us to rewrite equation (15) as

$$\vec{v}_{\vec{p}\sigma} = \frac{\hbar\vec{p}}{m} + \sum_{\vec{p}'} f^{\sigma\sigma}_{\vec{p}\vec{p}'}\nabla_{\vec{p}'}\delta n_{\vec{p}'\sigma} + \sum_{\vec{p}'} f^{a}_{\vec{p}\vec{p}'}\nabla_{\vec{p}'}\delta n_{\vec{p}'\bar{\sigma}}. \tag{16}$$

When one introduces $\nabla_{\vec{p}}\delta n_{\vec{p}\sigma} = (\mathrm{d}n^0_{\vec{p}\sigma}/\mathrm{d}\epsilon_{\vec{p}\sigma})\nabla_{\vec{p}}\epsilon_{\vec{p}\sigma}$ a self-consistent expression for the group velocity is obtained

$$\vec{v}_{\vec{p}\sigma} = \frac{\hbar\vec{p}}{m} - \sum_{\vec{p}'} f^{\sigma\sigma}_{\vec{p}\vec{p}'}\left(-\frac{\mathrm{d}n^0_{\vec{p}'\sigma}}{\mathrm{d}\epsilon_{\vec{p}'\sigma}}\right)\vec{v}_{\vec{p}'\sigma} - \sum_{\vec{p}'} f^{\sigma\bar{\sigma}}_{\vec{p}\vec{p}'}\left(-\frac{\mathrm{d}n^0_{\vec{p}'\bar{\sigma}}}{\mathrm{d}\epsilon_{\vec{p}'\bar{\sigma}}}\right)\vec{v}_{\vec{p}'\bar{\sigma}}. \tag{17}$$

In an isotropic system, the momentum and the group velocity are parallel and equation (17) leads to the renormalization of the effective mass, such that [12]

$$\vec{v}_{\vec{p}\sigma} = \frac{\hbar\vec{p}}{m^*_\sigma}. \tag{18}$$

m^*_σ is the value of the effective mass that incorporates the QP interaction and is spin dependent.

The spin σ current is defined in terms of the momentum carried by each bare QP multiplied by the deviation from equilibrium of its distribution function [17],

$$\vec{j}_\sigma = -e\sum_{\vec{p}}(\hbar\vec{p}/m)\delta n_{\vec{p}\sigma}. \tag{19}$$

By using equation (17) to express the QP momentum as a function of the group velocity, one can write

$$\vec{j}_\sigma = -e\sum_{vk}\left[\vec{v}_{\vec{p}\sigma} + \sum_{\vec{p}'} f^{\sigma\sigma}_{\vec{p}\vec{p}'}\left(-\frac{\mathrm{d}n^0_{\vec{p}'\sigma}}{\mathrm{d}\epsilon_{\vec{p}'\sigma}}\right)\vec{v}_{\vec{p}'\sigma} + \sum_{\vec{p}'} f^{\sigma\bar{\sigma}}_{\vec{p}\vec{p}'}\left(-\frac{\mathrm{d}n^0_{\vec{p}'\sigma}}{\mathrm{d}\epsilon_{\vec{p}'\sigma}}\right)\vec{v}_{\vec{p}'\bar{\sigma}}\right]\delta n_{\vec{p}\sigma}. \tag{20}$$

Changing the summation order in the last two terms, we obtain

$$\vec{j}_\sigma = -e\sum_{\vec{p}}\vec{v}_{\vec{p}\sigma}\left[\delta n_{\vec{p}\sigma} + \left(-\frac{\mathrm{d}n^0_{\vec{p}\sigma}}{\mathrm{d}\epsilon^0_{\vec{p}\sigma}}\right)\sum_{\vec{p}'} f^{\sigma\sigma}_{\vec{p}\vec{p}'}\delta n_{\vec{p}'\sigma}\right] - e\sum_{\vec{p}}\vec{v}_{\vec{p}\bar{\sigma}}\left(-\frac{\mathrm{d}n^0_{\vec{p}\bar{\sigma}}}{\mathrm{d}\epsilon^0_{\vec{p}\bar{\sigma}}}\right)\sum_{\vec{p}'} f^{\sigma\bar{\sigma}}_{\vec{p}\vec{p}'}\delta n_{\vec{p}'\bar{\sigma}}. \tag{21}$$

4. Differential spin current

The continuity equation for spin-σ particles, equation (14), correlates the time derivative of the total number of particles with the divergence of what should have been the particle current. When compared with the calculated value of the QP momentum transport, equation (21), one notices that the two expressions differ by an amount equal to

$$\vec{j}_d = e\sum_{\vec{p}}\vec{v}_{\vec{p}\bar{\sigma}}\left(-\frac{\mathrm{d}n^0_{\vec{p}\bar{\sigma}}}{\mathrm{d}\epsilon^0_{\vec{p}\bar{\sigma}}}\right)\sum_{\vec{p}'} f^{\sigma\bar{\sigma}}_{\vec{p}\vec{p}'}\delta n_{\vec{p}'\sigma} - e\sum_{\vec{p}}\vec{v}_{\vec{p}\sigma}\left(-\frac{\mathrm{d}n^0_{\vec{p}\sigma}}{\mathrm{d}\epsilon^0_{\vec{p}\sigma}}\right)\sum_{\vec{p}'} f^{\sigma\bar{\sigma}}_{\vec{p}\vec{p}'}\delta n_{\vec{p}'\bar{\sigma}}, \tag{22}$$

such that the continuity equation for spin σ is written as

$$\frac{\partial n_\sigma}{\partial t} + \nabla_{\vec{r}}(\vec{j}_\sigma + \vec{j}_d) = 0. \tag{23}$$

This signifies that the motion of spin σ entails also the motion of spin $\bar{\sigma}$, through the spin-dependent interaction which conditions a non-zero value of $\vec{j}_d$. This is a purely interactive effect, present independently of the Coulomb elastic scattering drag and is a sign of the opposite-spin correlations in the electron system.

Inserting the the solution to the transport equation (equation (12)) in equation (22) and linearizing in respect to the polarization we obtain

$$\vec{j}_d = e\frac{1}{m^*}\sum_{\vec{p}\vec{p}'} f^{\sigma\bar{\sigma}}_{\vec{p}\vec{p}'}(\vec{p}\cdot\vec{p}')\left(-\frac{\mathrm{d}n^0_{\vec{p}\sigma}}{\mathrm{d}\epsilon^0_{\vec{p}\sigma}}\right)\left(-\frac{\mathrm{d}n^0_{\vec{p}'\bar{\sigma}}}{\mathrm{d}\epsilon_{\vec{p}'\bar{\sigma}}}\right)(\vec{v}_\sigma - \vec{v}_{\bar{\sigma}}). \tag{24}$$

In this approximation, $m^*_\sigma = m^*_{\bar{\sigma}} = m^*$ is the spin-independent effective mass, while $\vec{v}_\sigma = -e\tau\vec{E}_\sigma/m^*$ is the spin-dependent drift velocity as determined by the spin-dependent driving field. By comparison with equation (2), the coefficient α is

$$\alpha = e\frac{1}{m^*}\sum_{\vec{p}\vec{p}'} f^{\sigma\bar{\sigma}}_{\vec{p}\vec{p}'}(\vec{p}\cdot\vec{p}')\left(-\frac{\mathrm{d}n^0_{\vec{p}\sigma}}{\mathrm{d}\epsilon^0_{\vec{p}\sigma}}\right)\left(-\frac{\mathrm{d}n^0_{\vec{p}'\bar{\sigma}}}{\mathrm{d}\epsilon_{\vec{p}'\bar{\sigma}}}\right). \tag{25}$$

On account of the δ function behaviour at the corresponding Fermi surfaces of $\left(-\frac{\mathrm{d}n^0_{\vec{p}\sigma}}{\mathrm{d}\epsilon^0_{\vec{p}\sigma}}\right)$ and $\left(-\frac{\mathrm{d}n^0_{\vec{p}\bar{\sigma}}}{\mathrm{d}\epsilon^0_{\vec{p}\bar{\sigma}}}\right)$, the opposite-spin effective interaction has to be estimated for momenta on different Fermi surfaces, $p = p_{F\sigma}$ and $p' = p_{F\bar{\sigma}}$. In this case, the difference $|\vec{p} - \vec{p}'|$ is

$$|\vec{p} - \vec{p}'| = \sqrt{p^2_{F\sigma} + p^2_{F\bar{\sigma}} - 2p_{F\sigma}p_{F\bar{\sigma}}\cos\theta}; \tag{26}$$

and $f^{\sigma\bar{\sigma}}_{\vec{p}\vec{p}'}$ admits a Fourier series expansion in terms of the angle θ between the directions of $\vec{p}$ and $\vec{p}'$. In two and three dimensions respectively, one can write

$$f^{\sigma\bar{\sigma}}_{\vec{p}\vec{p}'} = \begin{cases} \sum_l A_l(p_{F\sigma}; p_{F\bar{\sigma}})\mathrm{e}^{\mathrm{i}l\theta} & (d=2), \\ \sum_l B_l(p_{F\sigma}; p_{F\bar{\sigma}})P_l(\cos\theta) & (d=3) \end{cases} \tag{27}$$

where $P_l(\cos\theta)$ is the Legendre polynomial of order l. From this point on, the algebra is straightforward and we quote here just the final results

$$\gamma = \begin{cases} \dfrac{m^* p_{F\sigma}p_{F\bar{\sigma}}}{(2\pi\hbar^2)^2}A_1 & (d=2), \\ \dfrac{m^* p^2_{F\sigma}p^2_{F\bar{\sigma}}}{(2\pi^2\hbar^3)^2}B_1 & (d=3). \end{cases} \tag{28}$$

These results show that irrespective of dimensionality, α is proportional to the angular Fourier coefficient of the spin-dependent part of the effective Coulomb interaction.

5. Conclusions

In this paper, we demonstrate the existence of a dynamic spin coupling effect in a spin-polarized electron system that arises only when opposite-spin correlations are considered. On account of the opposite-spin effects, the 'apparent' spin-σ current is different from the spin-σ current associated with the QP momentum flow. In both two and three dimensions, the magnitude of the effect is proportional to the Landau phenomenological parameter that describes the angular dependence of the screened Coulomb interaction between two opposite spins and the relative drift velocity. A microscopic picture for this effect relies on obtaining an effective Hamiltonian for the interacting electron system that allows a representation of the interaction in terms of particle densities as in [18]. We are currently investigating this problem. Experimentally, the detection of this effect can be done in a semiconductor structure similar to the one proposed in [6] in which a paramagnetic region is sandwiched between two ferromagnetic contacts spin-polarized in the same direction. The measured current is the 'apparent' current $\vec{j}'_\sigma$ and its value should be different from the calculated value $\vec{j}_\sigma$.

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