Spin current in a superfluid Fermi-liquid in an electric field

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The interaction of magnetic moments of moving Fermi-particles with an external electric field creates a dissipation-free spin current in the superfluid state. In the superfluid ^{3}He-B the influence of the electric field can be revealed by experiments with spin supercurrent between two vessels with homogeneously precessing magnetization.

1. INTRODUCTION

It is well known[1,2] that the anisotropic interaction of an electric field **E**,

$$U_E = -bA_{\alpha i}A^*_{\alpha j}E_iE_j, \tag{1.1}$$

with the order parameter $A_{\alpha i}$ in superfluid phases of ^{3}He originates from the interaction between dipole moments of helium atoms induced by an external electric field. So, the value of the interaction strength

$$b \sim \frac{\alpha^2}{\mu^2}\left(\frac{R_E}{R}\right)^2 g_D$$

is determined by the value g_D of the dipole–dipole or the spin-orbital coupling. Here α is the polarizability of helium atoms, μ is the magnetic moment of helium nucleus, $(R_E/R)^2$ is some renormalization factor.

Another type of interaction with the electric field was recently proposed[3] in connection with experiments[4,5] on the spin superfluidity in ^{3}He-B. It was suggested that in a superfluid, neutral but magnetic (pairing with $S = 1$) Fermi liquid there is a spin supercurrent depending linearly on the electric field:

$$\mathbf{j}_z \sim \left(\nabla\alpha - 2\frac{[\vec{\mu}\mathbf{E}]}{\hbar c}\right). \tag{1.2}$$

Here α is the precession angle in NMR experiments, $\vec{\mu}$ is oriented in the z-direction. So, in experiments with the fixed spin supercurrent in a channel of length l between the two vessels with the homogeneously precessing magnetization,[3] the switching on the electric field gives the shift of the difference of precession angles

$$\delta\alpha \approx \frac{2\mu E}{\hbar c}l \approx 10^{-4}\,\text{rad},$$

for $E \approx 3\cdot 10^4$ V/cm. This value is of the order of the measurement accuracy.

In this paper we shall demonstrate that such spin current does exist due to the spin orbital interaction of usual type $[\mathbf{p}\vec{\mu}]\mathbf{E}/mc$. The expression for this current does not coincide with (1.2) but is of the same order.

2. HOMOGENEOUSLY PRECESSING MAGNETIZATION IN AN ELECTRIC FIELD

Using the gradient expansion of the Gor'kov equations we obtain an expression for the spin current in ^{3}He-B in an electric field [Appendix, (A16)]:

$$j_{\alpha i} = \frac{N_0 v_F^2\hbar^2}{30}(1 - Y(T))P_{\alpha i,\beta j}\left(\omega_{\beta j} - \frac{2\mu}{c\hbar}e_{\beta jk}E_k\right). \tag{2.1}$$

Here $N_0 = k_F m^*/2\pi^2$ is the density of states, v_F is the Fermi velocity, k_F is the Fermi momentum, $Y(T)$ is the Yosida function, $P_{\alpha i,\beta j} = -4\delta_{\alpha\beta}\delta_{ij} + R_{\alpha i}R_{\beta j} + R_{\alpha j}R_{\beta i}$, $R_{\alpha i}$ is the 3-dimensional rotation matrix determining the order parameter in B-phase, $\omega_{\alpha i} = \frac{1}{2}e_{\alpha\beta\gamma}R_{\beta j}\nabla_i R_{\gamma j}$ is the angular velocity of the rotation of the spin space.

This expression determines the dissipation-free spin current in the superfluid ^{3}He-B caused by the electric field. The appearance of the spin supercurrent under the electric field will be compensated for by a much stronger spin supercurrent due to gradients of the order parameter. So there will be created a complex distribution of the spin supercurrent in the vessel, depending on the distribution of an applied electric field, boundary conditions etc.

Let us obtain now the expression for the spin supercurrent due to an electric field in conditions of the homogeneously precessing magnetization.[3]

The spin current can be obtained from the free energy $\mathcal{F}$ by $\omega_{\alpha i}$ variation:

$$j_{\alpha i} = -\frac{\partial\mathcal{F}}{\partial\omega_{\alpha i}}. \tag{2.2}$$

So we get from (2.1) the expression for the gradient free energy (which, of course, can be obtained using the gradient expansion of Gor'kov equations up to the second order, see Refs. 6 and 7):

$$\mathcal{F}_\nabla = \frac{\chi}{2g^2}\left[c_\parallel^2\delta_{\alpha\beta}\delta_{ij} - (c_\parallel^2 - c_\perp^2)(R_{\alpha i}R_{\beta j} + R_{\alpha j}R_{\beta i})\right]$$
$$\times\left(\omega_{\alpha i} - \frac{2\mu}{c}e_{\alpha ik}E_k\right)\left(\omega_{\beta j} - \frac{2\mu}{c}e_{\beta jl}E_l\right), \tag{2.3}$$

(see Ref. 8). Here $c_\parallel^2$ and $c_\perp^2$ are the squares of spin-wave velocities:

$$c_\parallel^2 = \frac{4}{3}c_\perp^2 = \frac{4}{15}(1 - Y(T))\frac{\chi_n}{\chi}v_F^2,$$

χ_n and χ are the magnetic susceptibilities of normal and superfluid ^{3}He respectively, and g is the gyromagnetic ratio for ^{3}He-nuclei. Later we shall use units such that $\chi = g = 1$.

We rewrite (2.3) as follows:

$$\mathcal{F}_\nabla = \frac{1}{2}\left[c_\parallel^2\delta_{\alpha\beta}\delta_{ij} - (c_\parallel^2 - c_\perp^2)(\delta_{\alpha i}\delta_{\beta j} + \delta_{\alpha j}\delta_{\beta i})\right]\cdot$$
$$\cdot\left(\tilde{\omega}_{\alpha i} - \frac{2\mu}{c}R_{\alpha'\alpha}e_{\alpha' ik}E_k\right)\left(\tilde{\omega}_{\beta j} - \frac{2\mu}{c}R_{\beta'\beta}e_{\beta' jl}E_l\right), \tag{2.4}$$

where the components of the "angular velocity" $\tilde{\omega}_{\alpha i} = R_{\beta\alpha}\omega_{\beta i}$ in the rotating coordinate system are

$$\tilde{\omega}_{xi} = -\frac{\partial\alpha}{\partial x_i}\sin\beta\cos\gamma + \frac{\partial\beta}{\partial x_i}\sin\gamma,$$

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$$\tilde{\omega}_{yi} = \frac{\partial \alpha}{\partial x_i} \sin\beta \sin\gamma + \frac{\partial \beta}{\partial x_i} \cos\gamma, \tag{2.5}$$

$$\tilde{\omega}_{zi} = \frac{\partial \alpha}{\partial x_i} \cos\beta + \frac{\partial \gamma}{\partial x_i},$$

α, β, γ are Euler angles determining the matrix $R_{\alpha i}$ of the order parameter in B-phase, such that $\hat{R}(\alpha,\beta,\gamma) = \hat{R}_z(\alpha)\hat{R}_y(\beta)\hat{R}_z(\gamma)$.

We want to study the situation in the precessing ^{3}He-B (see Refs. 4, 5, and 8–11). In ^{3}He-B the dipole-dipole interaction keeps a partial degeneracy: the minimum of its energy is given by the condition

$$(1+\cos\Phi)(1+\cos\beta) = \frac{3}{2}, \tag{2.6}$$

where $\Phi = \alpha + \gamma$, and α is arbitrary. In this case the spin dynamics is the movement along this two-dimensional manifold with the coordinates α and β ($-1/4 \leqslant \cos\beta \leqslant 1$, $0 \leqslant \alpha \leqslant 2\pi$). In the case of the precession $\alpha = -\omega_p t$, where ω_p is the frequency of the precession, β, $\Phi = \text{const}$. So when we study low-frequency dynamics near the pure precession we can average the physical quantities over α.

In this way we compute the components of S_z-current (see Ref. 8):

$$\tilde{j}_{zk} = -\frac{\partial \mathcal{F}_\nabla}{\partial \psi_k}, \tag{2.7}$$

where $\psi_k = \nabla_k \psi = \nabla_k(\alpha + \omega_p t)$, and $\tilde{j}_{zk} = j_{zk} - j_{\xi k} = j_{zk}(1-\cos\beta) - \sin\beta(j_{xk}\cos\alpha + j_{yk}\sin\alpha)$. The final expression for the part of $\tilde{j}_{zk}$ linear in the electric field is:

$$\tilde{j}_{zz} = -4\frac{\mu}{c}(c_\parallel^2 - c_\perp^2)E_z \sin\Phi \sin^2\beta, \tag{2.8}$$

$$\tilde{j}_{zk} = -\frac{c_\parallel^2 - 3c_\perp^2}{2}(1-\cos\beta)\frac{2\mu}{c}e_{klz}E_l + (c_\parallel^2 - c_\perp^2)\frac{2\mu}{c}E_k \sin^2\beta \sin\Phi. \tag{2.9}$$

In (2.9) $k = x, y$.

3. ELECTRIC FIELD AND CRITICAL SPIN CURRENT

In this section we study the influence of an electric field on the dependence of the spin current in a channel on the gradient of α along this channel.[10,11]

Using Fomin's expression for j_{zk} (see Refs. 10, 11) and (2.9) we obtain:

$$\tilde{j}_{zk} = -(1-u)\Big[((1-u)c_\parallel^2 + (1+u)c_\perp^2)\alpha'_k - \frac{2\mu}{c}e_{klz}E_l\frac{c_\parallel^2 - 3c_\perp^2}{2} \mp \frac{2\mu}{c}E_k(c_\parallel^2 - c_\perp^2)\sqrt{3\Big(u+\frac{1}{4}\Big)}\Big], \tag{3.1}$$

where $u = \cos\beta$.

We study the case when the channel is parallel to y-axis: $\alpha'_y = \alpha'$.

One of the equations of low-frequency dynamics of ^{3}He-B (Ref. 11) is

$$\frac{\partial \alpha}{\partial t} = -\omega_L + \frac{1}{\omega_p}\frac{\delta \mathcal{F}}{\delta u}, \tag{3.2}$$

where ω_L is Larmor frequency, and the second one is the conservation law for S_z. Following Fomin we look for stationary solutions for which $\alpha' = \text{const}$ and $u = \text{const}$. In this way we obtain an equation for the α'–u dependence:

$$c_\perp^2 = c^2(1-u)(\alpha'\xi)^2 - (\alpha'\xi)\frac{2\mu\xi}{c}\Big[c^2\Big(-\frac{1}{2}\Big)E_x \pm (c_\parallel^2 - c_\perp^2)\frac{1-6u}{2\sqrt{4u+1}}\sqrt{3}E_y\Big], \tag{3.3}$$

where $\xi = c_\perp/\sqrt{\omega_p(\omega_p - \omega_L)}$, $c^2(u) = uc_\parallel^2 + (1-u)c_\perp^2$.

In the case $E = 0$ (Refs. 10, 11) there are two regimes: $0 \leqslant \alpha' \leqslant \alpha'_{c1}$ and $\alpha'_{c1} \leqslant \alpha' \leqslant \alpha'_{c2}$, where $\alpha'_{c1}\xi = \sqrt{4c_\perp^2/(5c_\parallel^2 - c_\perp^2)}$ and $\alpha'_{c2}\xi = 1$. In the case $E \neq 0$ there is only one regime and α'–u dependence (as well as the $\tilde{j}_{zy}$–α' dependence) is smooth.

As for the spin current the dependence of $\tilde{j}_{zy}$ on α' is given by (3.1), where u can be obtained from (3.3). For $\alpha'\xi \ll 1$ (and consequently $u + 1/4 \ll 1$) we obtain from (3.1), (3.3):

$$\tilde{j}_{zy} = \frac{\mu}{c}E_x \cdot \frac{5}{2}c^2\Big(-\frac{1}{2}\Big) - \Big\{\frac{5}{2}c^2\Big(\frac{5}{8}\Big) \mp \frac{75}{8}\frac{(c_\parallel^2 - c_\perp^2)^2}{c_\parallel^2}\Big(\frac{\mu}{c}\xi E_y\Big)^2\Big\}\alpha'. \tag{3.4}$$

We see that spin current exists when there is no gradient of α and the electric field is perpendicular to the magnetic field and the channel. Moreover the slope $d\tilde{j}/d\alpha'$ (when $\alpha' = 0$) is slightly transformed. The small parameter of this problem is $\mu E\xi/c$.

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APPENDIX

Using the gradient expansion of Gor'kov equations (see, for instance, Refs. 6, 7) we shall compute the Green's functions of the system, and then we shall obtain the microscopic expression for the spin current. We consider ^{3}He-B not to be moving, i.e., the velocity of the normal component $\mathbf{v}_n = 0$.

Let us write the Gor'kov equations bearing in mind the spin-orbit coupling of the usual type $\mu\vec{\sigma}[\mathbf{Ep}]/m^*c$:

$$\{i\omega + \mu(\mathbf{r}) - \frac{1}{2m^*}(\mathbf{k} - i\nabla)^2 - \mathbf{B}\vec{\sigma} + \frac{\mu}{m^*c}\vec{\sigma}[\mathbf{E}, \mathbf{k} - i\nabla] - \delta\epsilon(\mathbf{k},\mathbf{r})\}G(\mathbf{k},\mathbf{r},\omega) - \Delta(\mathbf{k} - i\nabla, \mathbf{r})F^+(\mathbf{k},\mathbf{r},\omega) = 1, \tag{A1}$$

$$\{-i\omega + \mu(\mathbf{r}) - \frac{1}{2m^*}(\mathbf{k} - i\nabla)^2 - \mathbf{B}\vec{\sigma}^T - \frac{\mu}{m^*c}\vec{\sigma}^T[\mathbf{E}, \mathbf{k} - i\nabla] - \delta\epsilon^T(-\mathbf{k},\mathbf{r})\}F^+(\mathbf{k},\mathbf{r},\omega) + \Delta^+(\mathbf{k} - i\nabla, \mathbf{r})G(\mathbf{k},\mathbf{r},\omega) = 0.$$

Here

$$\omega = (2n+1)\pi T, \quad \mathbf{B}\vec{\sigma} = -\frac{1}{2}|g|H_z\sigma_z,$$

$\mathbf{E}$ is the electric field, g is the gyromagnetic ratio, $\mu(\mathbf{r})$ is the chemical potential, $\hbar = 1$, μ is the magnetic moment of the

^{3}He-nucleus which almost exactly coincides with the anomalous magnetic moment of a neutron, that is why we take the spin-orbit coupling $\mu\vec{\sigma}[\mathbf{Ep}]/m^*c$ but not $\mu\vec{\sigma}[\mathbf{Ep}]/2m^*c$ (see Ref. 12).

We use the Green functions

$$G(\mathbf{k},\mathbf{r}) = \int \exp[-i\mathbf{k}(\mathbf{r}-\mathbf{r}')]G(\mathbf{r},\mathbf{r}')d(\mathbf{r}-\mathbf{r}'),$$

$$F^+(\mathbf{k},\mathbf{r}) = \int \exp[-i\mathbf{k}(\mathbf{r}-\mathbf{r}')]F^+(\mathbf{r},\mathbf{r}')d(\mathbf{r}-\mathbf{r}') \qquad \text{(A2)}$$

and omit their dependence on frequency.

For the order parameter of the B-phase

$$\Delta(\mathbf{k},\mathbf{r}) = \Delta_0(T)i\sigma_\alpha R_{\alpha i}(\mathbf{r})\frac{k_i}{k_F}\sigma_y e^{i\Phi}, \qquad \text{(A3)}$$

where $\sigma_\alpha = (\sigma_x,\sigma_y,\sigma_z)$ are Pauli matrices, the equality

$$\Delta(\mathbf{k},\mathbf{r}) = -3g\int \frac{d\Omega_{\mathbf{k}'}}{4\pi}\frac{\mathbf{k}\mathbf{k}'}{k_F^2}T\sum_\omega F(\mathbf{k}',\mathbf{r}) \qquad \text{(A4)}$$

holds.

The Fermi-liquid corrections are

$$\delta\hat{\varepsilon}(\mathbf{k},\mathbf{r}) = \delta\varepsilon + \vec{\nu}\vec{\sigma},$$

$$\delta\varepsilon = \mathrm{Sp}'\sum_{\mathbf{k}'} f(\mathbf{k}+\frac{\mu}{c}[\mathbf{E}\vec{\sigma}],\mathbf{k}'+\frac{\mu}{c}[\mathbf{E}\vec{\sigma}'])T\sum_\omega \delta\hat{G}(\mathbf{k}',\mathbf{r},\omega), \qquad \text{(A5)}$$

$$\vec{\nu} = \frac{1}{4}\mathrm{Sp}'\sum_{\mathbf{k}'} z(\mathbf{k}+\frac{\mu}{c}[\mathbf{E}\vec{\sigma}],\mathbf{k}'+\frac{\mu}{c}[\mathbf{E}\vec{\sigma}'])T\sum_\omega \vec{\sigma}'\delta\hat{G}(\mathbf{k}',\mathbf{r},\omega),$$

$\delta\hat{G}$ is the deviation of the Green function, Sp$'$ is the trace over indices of $\vec{\sigma}'$ and $\delta\hat{G}(\mathbf{k}')$. Except for the mass renormalization for our purposes only the term with $l=1$ in $\vec{\nu}$ is necessary (if we neglect higher harmonics Z_l with odd $l\geqslant 3$):

$$z(\mathbf{k},\mathbf{k}') = z_1(\hat{\mathbf{k}},\hat{\mathbf{k}}') = (2N_0)^{-1}Z_1(\hat{\mathbf{k}},\hat{\mathbf{k}}'). \qquad \text{(A6)}$$

We can expand (A1) in powers of ∇ and single out the terms G_i^0, F_i^{+0} of this series in the zero field and the terms G_i^E, F_i^{+E} depending linearly on E:

$$\mathcal{G} = \mathcal{G}_0 + \mathcal{G}_1 + \ldots, \quad \mathcal{G}_i = \mathcal{G}_i^0 + \mathcal{G}_i^E,$$

where

$$\mathcal{G} = \begin{pmatrix} G \\ F^+ \end{pmatrix}. \qquad \text{(A7)}$$

Using this expansion we obtain from (A1):

$$\mathcal{G}_0^0 = D^{-1}E^+\begin{pmatrix} 1 \\ 0 \end{pmatrix}, \qquad \text{(A8a)}$$

$$\mathcal{G}_1^0 = -D^{-1}E^+(R_1 + C_1^0)\mathcal{G}_0^0, \qquad \text{(A8b)}$$

$$\mathcal{G}_0^E = -D^{-1}E^+(\frac{\mu}{m^*c}\mathrm{S}[\mathbf{Ek}] + C_0^E)\mathcal{G}_0^0, \qquad \text{(A8c)}$$

where

$$E = \begin{pmatrix} \varepsilon & -\Delta \\ \Delta^+ & \varepsilon^* \end{pmatrix}, \qquad \text{(A9)}$$

$$D = EE^+ = |\varepsilon|^2 + \Delta\Delta^+, \qquad \text{(A10)}$$

$$\varepsilon = i\omega + \mu - \frac{k^2}{2m^*}, \qquad \text{(A11)}$$

$$R_1 = \begin{pmatrix} -\frac{\mathbf{k}\nabla}{im^*} & -\frac{\partial\Delta}{\partial\mathbf{k}}\frac{\nabla}{i} \\ \frac{\partial\Delta^+}{\partial\mathbf{k}}\frac{\nabla}{i} & -\frac{\mathbf{k}\nabla}{im^*} \end{pmatrix}, \qquad \text{(A12a)}$$

$$\mathrm{S} = \begin{pmatrix} \sigma & 0 \\ 0 & -\sigma^T \end{pmatrix}, \qquad \text{(A12b)}$$

$$C = \begin{pmatrix} -\delta\varepsilon(\mathbf{k},\mathbf{r}) & 0 \\ 0 & -\delta\varepsilon^T(-\mathbf{k},\mathbf{r}) \end{pmatrix}, \qquad \text{(A12c)}$$

and C_1^0, C_0^E are the terms of the corresponding series [see (A14) below].

The spin current density can be expressed in terms of the Green function:

$$j_{\alpha i}(\mathbf{r}) = \left\{\int \frac{d\mathbf{k}}{(2\pi)^3}\frac{k_i}{m}T\sum_\omega \frac{1}{4}\mathrm{Sp}(\sigma_\alpha\delta G(\mathbf{k},\mathbf{r})) + \text{H.c.} + \frac{\mu}{2mc}e_{\alpha ik}E_k n\right\}\left(1+\frac{Z_1}{12}\right)\frac{m}{m^*}. \qquad \text{(A13)}$$

Here n is the concentration of particles.

From (A5) and (A13) we obtain:

$$\nu_\alpha(\mathbf{k},\mathbf{r}) = \frac{z_1}{2(1+Z_1/12)}m^*\frac{k_i + (\mu/c)[\mathbf{E}\vec{\sigma}]_i}{k_F^2}j_{\alpha i}, \qquad \text{(A14)}$$

and then from (A13):

$$j_{\alpha i} = \left(1+\frac{Z_1}{12}\right)\frac{m}{m^*}j_{\alpha i}^0 - \frac{1}{12}Z_1\left(\delta_{\alpha\beta}\delta_{ij} + \frac{1-Y(T)}{5}P_{\alpha i,\beta j}\right)j_{\beta j}, \qquad \text{(A15)}$$

where j is the spin current, j^0 is the spin current without Fermi-liquid corrections, the tensor $P_{\alpha i,\beta j} = -4\delta_{\alpha\beta}\delta_{ij} + R_{\alpha i}R_{\beta j} + R_{\alpha j}R_{\beta i}$, $Y(T)$ is Yosida function:

$$Y(T) = \int_{-\infty}^{+\infty}\frac{1}{4T}\mathrm{sech}^2\frac{\varepsilon}{2T}d\xi,$$

$Y(T)=0$ when $T=0$ and $Y(T)=1$ when $T\geqslant T_c$ ($\varepsilon=\sqrt{\xi^2+\Delta\Delta^+}$ is the energy of elementary excitations).

For $Z_1=0$ we obtain from (A8b), (A8c), and (A13) the expression for the spin current:

$$j_{\alpha i} = \frac{N_0 v_F^2}{30}(1-Y(T))P_{\alpha i,\beta j}(\omega_{\beta j} - \frac{2\mu}{c}e_{\beta jk}E_k). \qquad \text{(A16)}$$

Here $N_0 = k_F m^*/2\pi^2$ is the density of states (for one spin component).

It is instructive to point out also the expression for the spin current in an arbitrary p-pairing superfluid phase in an electric field near T_c:

$$j_{\alpha i} = \frac{7\zeta(3)}{(2\pi T_c)^2}\frac{N_0 v_F^2}{30}\Big\{\delta_{ij}A_{\alpha n}A^*_{\varphi n} + A_{\alpha i}A^*_{\varphi j} + A_{\alpha j}A^*_{\varphi i} - \delta_{\alpha\varphi}(\delta_{ij}A_{\beta n}A^*_{\beta n} + A_{\beta i}A^*_{\beta j} + A_{\beta j}A^*_{\beta i})\Big\}(\omega_{\varphi j} - \frac{2\mu}{c}e_{\varphi jq}E_q),$$

if the order parameter is $\Delta = i\sigma_\alpha\sigma_y A_{\alpha i}k_i/k_F$ and $\Delta_j A_{\mu i} = e_{\mu\varphi\psi}\omega_{\varphi j}A_{\psi i}$.

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