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Dipole effects in spin dynamics of spin-polarized quantum systems

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We consider magnetic dipole-dipole interaction in highly polarized Fermi liquids with an emphasis on the effect of zero-temperature transverse relaxation on longitudinal processes and spin-wave instabilities. *

1. INTRODUCTION

One of the most interesting recent developments in physics of spin-polarized Fermi liquids was a prediction [1, 2, 3] and observation [4, 5] of peculiar zero-temperature attenuation in transverse spin dynamics. The transverse relaxation time, $\tau_\perp$, in contrast to all other Fermi-liquid relaxation processes, does not increase at low temperatures as $1/T^2$, but remains finite, $\tau_\perp \sim (N v_F \sigma)^{-1} (T_F/\beta H)^2$ even at $T \to 0$ (N is the density of fermions with magnetic moment β, cross-section σ, Fermi temperature and Fermi velocity T_F and v_F). Since this relaxation is the only low-frequency zero-temperature relaxation mechanism in *pure* Fermi liquids, it is worth studying whether this mechanism is coupled to and affects other Fermi-liquid processes, including the longitudinal ones.

We looked at two possible sources of coupling between longitudinal an transverse processes: magnetic dipole-dipole interaction and inhomogeneous coupling caused by gradient terms. Below we report the effect of dipole-dipole coupling of longitudinal and transverse spin processes on longitudinal relaxation and spin-wave instabilities at ultralow temperatures.

2. RESULTS

2.1. Sound attenuation

First, we studied the possibility of (zero-) sound attenuation at $T = 0$ which can arise because of magnetic dipole coupling between the sound oscillations and transverse spin dynamics. In spin-polarized systems, sound (density) oscillations are accompanied by the oscillations of the longitudinal component of the magnetic moment distribution. The magnetic dipole-dipole interaction, which can be quite strong in highly polarized systems [6], couples these oscillations to the oscillations of transverse component of magnetization thus transferring the attenuation from transverse to longitudinal channels. We derived the set of corresponding coupled Fermi-liquid equations and calculated the contribution to the sound attenuation that is associated with the zero-temperature transverse attenuation.

The effective zero-temperature attenuation in the longitudinal channel $\tau_{eff}\,(T = 0)$ should differ from $\tau_\perp$ by the factor $(E_d/T_F)^2$ where the dipole energy $E_d = \beta^2 Z^2 m^{3/2} {T_F}^{3/2}/\hbar^3$, and the microscopic parameter Z describes the difference between Fermi liquid and Fermi gas. We solved the kinetic equation for (zero-) sound oscillations, coupled via small dipole terms to the equation of transverse spin dynamics.

As a result, the sound frequency acquired an imaginary part (attenuation) equal, at $T = 0$, to

$$\omega'' = \frac{(\hbar k v_F)^2}{32\pi^2 \tau_\perp} \left[\frac{{F_0}^{(s)}}{{F_0}^{(s)} - {F_0}^{(a)}}\right]^2 \frac{{E_d}^2}{{T_F}^4} \Phi \qquad (1)$$

where ${F_0}^{(s,a)}$ are the zero harmonics of the symmetric and antisymmetric Landau functions, $s v_F = \omega/k$ is the sound velocity, the function $\Phi\,(\mathbf{k}/k, s)$ has the form

$$\Phi\left(\frac{\mathbf{k}}{k}, s\right) = \frac{k^2 - {k_z}^2}{k^2} \left[\frac{{k_z}^2}{k^2}\Gamma_1 + \Gamma_2\right] \qquad (2)$$

and $\Gamma_{1,2}(s)$ are some positive dimensionless functions of s without any distinct interesting features. As expected, the attenuation depends on the angle θ between the z-axis (the polarization axis) and the direction of the wave vector $\mathbf{k}$, $k_z = k \cos\theta$, and is highly anisotropic.

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2.2. Effective longitudinal relaxation

Comparison of this equation with a standard equation for temperature-driven sound attenuation, $\gamma = \gamma_{cl}\left[1 + (\hbar\omega/2\pi T)^2\right]$, allows us to determine the effective anisotropic field-driven relaxation time for longitudinal channel

$$\tau^{-1}{}_{eff}(\theta) = \frac{1}{8}\tau_\perp{}^{-1}\left(\frac{E_d \beta H}{T_F{}^2}\right)^2 \Phi_1(\theta, s), \quad (3)$$

where

$$\Phi_1 = \left(\frac{F_0{}^{(s)}}{F_0{}^{(s)} - F_0{}^{(a)}}\right)^2 \frac{\Phi(\theta, s)}{\xi(s)}, \quad (4)$$

and $\xi(s)$ is some cumbersome featureless function of s. Then we can introduce an effective field-driven viscosity as

$$\eta_{eff} = \rho v_F{}^2 \tau_{eff}\left(1 + F_1{}^{(s)}/3\right)/5 \quad (5)$$

2.3. Spin-wave instabilities

The non-linear coupling between longitudinal and transverse processes can be strongly enhanced by Castaing instability [7] in transverse spin dynamics in an inhomogeneous setting.

We analyzed the dipole effect on the Castaing instabilities in spin dynamics in the presence of large magnetization gradient ∇M. Without dipole terms, the onset of this instability is determined by the equation $k^2 = \mu k_i \nabla_i M$. Though the effect of dipole interaction is quite small (all additional dipole terms in this equation have the order E_d/T_F), this equation changes its structure and becomes highly anisotropic by acquiring terms of the form $k_z{}^2$, $\mu k_z \nabla_z M$, $(\mu \nabla_z M)^2$, and $(\mu \nabla M)^2$ (we will not give here the cumbersome coefficients).

Though the Castaing instability occurs in the transverse spin dynamics, its important feature is that the Leggett parameter μ is proportional to the longitudinal relaxation time $\tau_{\|}$, and not $\tau_\perp$, and, therefore, increases as $1/T^2$. This means that at low temperatures the onset of instability happens at larger and larger wave vectors. This instability exists, at least in its usual form, as long as $1/\tau_{\|} >> kv_F$ and the polarization gradient creates the diffusion spin current. This condition provides the lower limit for the temperature at which the instability can be observed, $T_F >> T >> T_F/x^{1/3}(a/L)^{1/4}$ (a is the atomic size, L is the spatial scale of the polarization gradient, and the molar concentration of fermions $x \sim 1$ for pure ^3He).

At lower temperatures one should neglect the collision integral (diffusion current) in the dynamic equation for longitudinal magnetization. As a result, the longitudinal diffusion spin current disappears, and the usual coupling between longitudinal and transverse equation should not lead to the instability any more. However, the dipole coupling between longitudinal and transverse channels ensures the presence of the finite effective relaxation time, τ_{eff}, and, therefore, the diffusion current in the longitudinal equation. This restores the Castaing instability even at very low temperatures at $k^2 = \mu_{eff} k_i \nabla_i M$ where the effective Leggett parameter contains the relaxation time τ_{eff} (3) instead of $\tau_{\|}$ under the condition $1/\tau_{eff} >> kv_F$

3. CONCLUSIONS

We developed a theory of dipole coupling between longitudinal and transverse spin dynamics processes in spin-polarized Fermi liquids with an emphasis on the transfer of zero-temperature transverse attenuation into longitudinal channels. We calculated the effective zero-temperature (zero-) sound attenuation, and, on its basis, the effective longitudinal relaxation time, and viscosity. We determined the effect of dipole coupling on Castaing instabilities and demonstrated the existence of the instability even at very low temperatures when the usual longitudinal relaxation time becomes infinite. In addition, the dipole interaction makes all the processes in spin-polarized systems highly anisotropic.

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