Possible origin of the unusual peak observed in the spin-diffusion coefficient of ^{3}He films

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Abstract

We show a theoretical result that yields the existence of a peak in the spin diffusion coefficient as a function of density ($D_{\rm spin}(n)$) in a dilute two dimensional Fermi liquid. We argue that may be an explanation for the unusually peaked $D_{\rm spin}(n)$ observed in ^{3}He films[1].

Key words: Quantum fluids; Fermi liquids; Helium 3; two dimensions

Recent measurements of the spin diffusion coefficient ($D_{\rm spin}$) in ^{3}He films revealed an unexpected peak as a function of the density (n)[1]. While the expected behaviour would be a monotonic decrease of $D_{\rm spin}$ as n increases, the observed result consists of a dramatic increase for low densities followed by a plateau-like region where $D_{\rm spin}$ varies little and then a monotonic decrease.

A theoretical attempt to understand this result has been provided in [2], and while it is not concerned with giving a full match for the data, the conditions under which the data are fit in the pertinet regions are encouraging. We want to state these conditions at the outset, by reproducing a plot from [2] in Fig.1. We see that reasonable agreement with the experimental set of points is obtained in the side regions, where $D_{\rm spin}$ varies more with n. The fitting adjusts two parameters in the theoretical result: the absolute value of $D_{\rm spin}$ (vertical scale), and a hard-disk radius (a_s). Adjusting one temperature curve yields all other curves without additional adjusts and the value of a_s necessary for the fit agrees with those obtained in measurements of the spin susceptibility taken from other experiments ($a_s \sim$ 0.7 Å).

In this short communication, we further discuss the physical origin that may be underlying such a result.

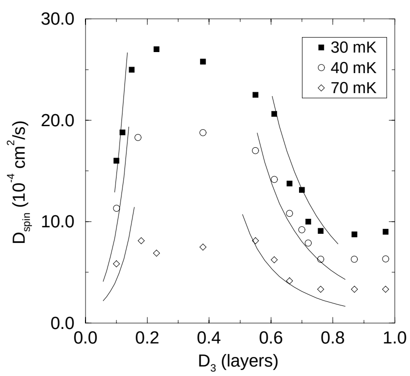

Fig. 1. Spin diffusion coefficient as measured in Ref.[1] (points) and theoretical fitting (solid lines). D$_3$ stands for the density n in proper “coverage” units.

The theory relies on quite general statements that hold for a Fermi liquid in two spatial dimensions (2D).

In Refs.[2,3] subside has been given for the relation of such a peaked behaviour in $D_{\rm spin}(n)$ and the existence of a regime of the 2D Fermi liquid that conserves spin current. This may be understood as follows. The experiment measures the spin relaxation time τ related to the scattering rate $\omega = 1/\tau = \omega_{DFL} + \omega_{DSB} + \omega_{\eta FL} + \omega_{\eta SB} + O(3)$, where FL stands for contributions from purelly internal Fermi liquid processes while SB indicates mechanisms from external sources, like

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the scattering with the substrate; ω_D is due solely to diffusional processes and ω_η is a "spin-viscous" rate, which is the next order term in the scattering integral. Higher order rates are represented by $O(3)$. Here we assume that $\omega_{\eta FL}$ and ω_{DSB} are different from zero bounded quantities for the densities studied and that ω_{DFL} may vanish for some value of the density, as it has been shown in Ref.[2]. With these assumptions and using the results of [2] we can write ω_{DFL} explicitly and keep the leading order scattering frequencies,

$$\omega = \frac{|\Gamma_0^k(\pi)|^2}{f(n) + |\Gamma_0^k(\pi)|^2 \Delta\tau_D} + \omega_{\eta FL} + \omega_{DSB}, \qquad (1)$$

where $\Delta\tau_D$ is bounded for all densities, $f(n) = 3\hbar/4n\pi N(0) z^4 (T/T_F)^2 \ln(T/T_F)$, $N(0)$ and z are the density of states and the quasiparticle residue at the Fermi circle, (T_F) T is the (Fermi) temperature, and $\Gamma_0^k(\theta) \equiv \Gamma_{\uparrow\downarrow\downarrow\uparrow}^k(\theta)$ is the $\omega = 0$ limit of the vertex function, which relates to the scattering amplitude of a pair of Fermions with opposite momenta and spin (a "Cooper-like" pair). In 2D, such head-on collisions are major in preventing spin current conservation, as it may be seen in Fig.2 by noting that a head-on collision ($\theta = \pi$) has infinitely more phase space for outgoing momenta. This reflects in (1): ω_{DFL} is zero

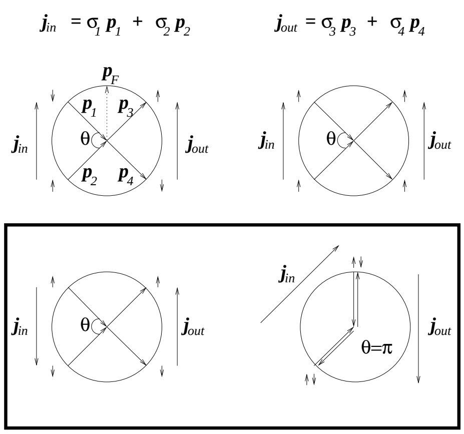

Fig. 2. Fermi circles with possible collision processes; the rectangle marks those which prevent conservation of spin-current ($\boldsymbol{j}_{in} \neq \boldsymbol{j}_{out}$).

when $\Gamma_0^k(\pi) = 0$.

The physics of 2D collisions is a bit more involved than the simple picture given by the Fermi circles. In particular, an antibound state exists for repulsive pair interactions, which is a consequence of the finite density of states for small momenta characteristic of 2D.[4] Define $g \equiv -[\ln(\mathrm{D}_3(\pi a_s/5)^2)]^{-1}$ and the interaction vertex (which is the *other* limit, $k = 0$ of the full vertex) is given by $e^{-1/g}\sin^2(\theta/2) - g/[1 - g\ln\cos^2(\theta/2)]$. The exponential contribution is due to the presence of the antibound state, and is peaked at $\theta = \pi$. Using an integral equation relating the two limits[2] one solves for $\Gamma_0^k(\theta)$ and then determines whether $\Gamma_0^k(\pi)$ has roots and for which densities. It is surprising that the exponentially small contribution from the bound state can lead to such a different behavior in 2D. Fig.3 presents a study for the existence of roots in $\Gamma_0^k(\pi) = 0$ made by simply replacing $e^{-1/g} \to \lambda e^{-1/g}$. It is clear that roots exist if the intensity of the bound state's contribution is $\lambda > 0.65$.

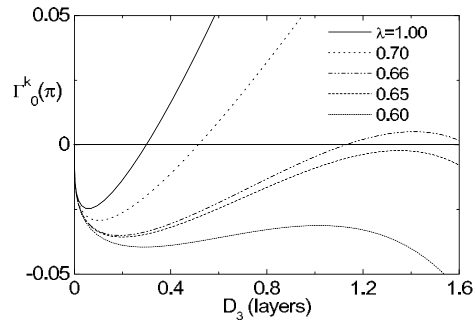

Fig. 3. Vertex function at π for different values of the bound state's "intensity" λ.

For the actual value of $\lambda = 1$, the root occurs for $\mathrm{D}_3 \sim 0.3$ layers. This makes $\omega_{DFL} \to 0$ and the sum $\omega_{\eta FL} + \omega_{DSB}$ becomes dominant around this density. In the plot given by Fig.1 the contributions of these two terms where not included, hence a divergence in the relaxation time ($D_{\rm spin}$) results. In order to see whether spin viscosity or diffusion by the substrate or both lead to the full observed behavior, calculations of $\omega_{\eta FL}$ and ω_{DSB} as a function of D_3 are necessary. Yet, the existence of a peak appears to have its origin on the physics shortly described here.

Acknowledgements

The author thanks FAPESP, CNPq, and the LT23 committee for financial support and the hospitality of Marcos Degani at Universidade São Francisco, Itatiba, SP, where part of this work has been developed.

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