

BOUNDARY CONDITIONS AND SPIN WAVES IN SPIN-POLARIZED QUANTUM GASES

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Macroscopic boundary conditions are studied for spin dynamics in spin-polarized quantum gases. The constants in the boundary conditions are related to all possible microscopic processes (scattering, depolarization, sticking, etc.). Important changes start with the formation of an absorbed boundary layer at low temperatures.

1. INTRODUCTION

Spin-polarized quantum gases are usually studied experimentally at low temperatures and densities when the mean free paths are relatively long and boundary effects may become noticeable (see, e.g. review (1) and references therein). The interaction of gas particles with the walls is usually studied in terms of individual scattering probabilities or in the frames of kinetic equation (see, e.g., (2)). However, some of the major phenomena in quantum gases, including spin waves, are often described macroscopically in the frames of "hydrodynamic" approach. Therefore, it seems important to bridge the gap between kinetic and hydrodynamic boundary conditions, and to understand a microscopic meaning and an order of magnitude of macroscopic boundary constants.

The simplest macroscopic (hydrodynamic) boundary condition for spin dynamics has the form $0 = M + \Lambda n_{\perp} \nabla_{\perp} M$, where M is the density of magnetic moment, n_{\perp} is the unit vector normal to the boundary and directed into the gas. The parameter Λ contains all the information about the boundary scattering. The situations occurring most often correspond either to $\Lambda \rightarrow \infty$ (zero magnetic flow through the boundary; in quantum gases it occurs, e.g., for $H \uparrow$ at relatively high temperatures) or to $\Lambda \rightarrow 0$ (complete magnetic relaxation on the walls; such case takes place for spin waves in ^3He systems when there is a localized absorbed helium layer on the walls; for details see Ref.(1)). The question is to formulate conditions when it is possible to express all relevant boundary information through the single constant Λ , and to relate Λ to microscopic boundary parameters. Another interesting question is what happens with $H \uparrow$ when the temperature is lowered, mean free paths increase, collisions with the walls become more and more important, and, eventually a noticeable surface absorption of hydrogen atoms begins. Some experimental results have recently been reported, (3). With intermediate values of Λ , the positions and widths of spin-wave resonances, e.g., in Ref.(3), are described by the equation $\phi(x=0) + \Lambda \phi'_x(x=0) = 0$, where ϕ is the Airy function describing the density of the magnetic moment,

$$M(x) = -M_0 \phi\left\{[-x + (\omega\tau T/Gm)(1 + \Omega^2 \tau^2)] / (1 + \Omega\tau)\right\} / [-iG]^3,$$

M_0 is the scaling factor, τ is the bulk exchange relaxation time, Ω is the (bulk) molecular field frequency, and G is the magnetic field gradient.

2. SURFACE SCATTERING

At low temperatures (but higher than the beginning of intensive absorption) the main mechanism of interaction with non-magnetic walls is scattering giving rise to some additional spin relaxation and spin diffusion along and perpendicular to the wall. If the walls are located at $x = 0$ and $x = L$, then the integration of kinetic equation (1) with an additional collision integral corresponding to the boundary scattering leads to the following general macroscopic equations in M and spin current J_{\perp} :

$$(\partial/\partial t)M + (\partial/\partial r_{\perp})J = -M_{\perp}(\tau) \{ \delta(x) + \delta(x-L) \} / \tau^*,$$

$$(\Omega + \nu/\tau)J + i(T/m)(\partial/\partial r_{\perp})M = -i\ell(T/m) \{ (1/D -$$

$$- 1/D')n_{\perp}(n_{\perp}J_{\perp}) + J_{\perp}/D' \} [\delta(x) + \delta(x-L)],$$

where τ^* is the surface spin non-conserving (e.g., dipole) relaxation time, D and D' are the (surface) spin diffusion coefficients along and perpendicular to the surface, and $\ell \geq a$ is the dimensionality factor. Then the coefficient Λ in the macroscopic boundary condition is equal to

$$\Lambda = (i\ell) \{ (T/m)q^2 / (\Omega + \nu/\tau)D + (m/T)(\Omega + \nu/\tau)/\tau^* \}$$

where q is the component of the wave vector along the boundary, $k = q + k_{\perp}$.

The above description is valid only if τ^* and mD/T are much smaller than the bulk relaxation time τ , the effective "thickness" of the boundary layer is small, $k_{\perp} \ell \ll 1$, and the boundary condition on the "outer" side of the boundary (i.e.,

deep inside the wall) corresponds to the absence of spin current. The last condition is violated in case of magnetic and, to some extent, metal walls, and the first - if the density of magnetic "imperfections" of the wall is high.

If there are very few magnetic impurities or centers on the wall, the term with τ^* is less significant than the first one where D characterizes general imperfections of the wall and the difference of the reflection from the specular one [in simplest cases, $D \sim \lambda T/m(1-p)$, and p is the coefficient of specularity of reflection]. This term is responsible for the temperature dependence (or for the lack of it - while D is still large) of spin wave resonances. Certainly, this does not depend on whether the system is in hydrodynamic or Knudsen regime. From this point of view, the surface scattering is somewhat analogous to the elastic scattering by non-magnetic impurities in the bulk, which results only in some renormalization of the mass- (and, therefore, spin-) diffusion coefficient while the molecular field frequency, Ω , responsible for the existence of spin waves and the position of resonances, remains unchanged. With lowering temperatures Λ usually remains imaginary, and practically does not change. The change in density (and a possible transition to the Knudsen regime) does not affect $\Omega\tau$, but changes the surface contribution determined by the dimensionless parameter $\Omega Dm/T$.

3. INTERACTION WITH THE ABSORBED LAYERS

The formation of the relatively dense boundary layers by absorbed hydrogen particles at low temperatures leads to two effects: the set of boundary constants becomes different, and the number of equations doubles reflecting the appearance of additional macroscopic variables: the surface density of the magnetic moment m and the surface spin current j .

If one neglects the coupling of bulk and surface modes which may be weak because of possible large difference in densities and characteristic frequencies) then, effectively, the boundary conditions remain the same as above, but with considerable changes in the parameters involved. The most important change is the appearance of a large imaginary part in the coefficient $D = D' + iD''$ (the real part in Λ). This results in some effective increase in a spin waves attenuation, and was observed experimentally (3).

The origin of the coefficient D'' is, in fact, not a dissipative, but a dephasing one. Since the boundary layer consists of the same particles as the bulk of the gas, the exchange with the boundary layer leads to some renormalization - near the surface - of the molecular field

Ω . The simplest way to incorporate the "surface" molecular field $\Omega_S \sim \alpha n/m$ (n is the density of these 2D layers with spin polarization α) into the above equations is to substitute D by a renormalized value with a large imaginary part, $D \rightarrow D/(1 - im\Omega_S/TD)$. The large dephasing associated with this imaginary part is more noticeable experimentally than all other changes: it leads to a broadening of the lines which were very narrow before (τ and τ^* are very large), while all other effects lead only to (small) changes of the order $n/\lambda N$.

At even lower temperatures, one should also take into account the coupling of the surface and bulk modes. This process is much more complicated, and will be discussed separately. However, it is worth mentioning that here one deals with two different frequency regimes corresponding to different degrees of equilibration between surface and bulk variables during the oscillation. As a result, one will observe not only changes in values of boundary parameters, but also some frequency dispersion of all characteristics.

4. SUMMARY

The macroscopic boundary conditions for the spin waves in spin-polarized quantum gases are discussed. The relations are established between the coefficients in macro- and microscopic boundary conditions, thus allowing the explanation of the observed temperature and density dependencies of spin-wave resonances. The most interesting effects occur when the absorbed boundary layer starts to form leading to an appearance of the surface molecular field and to broadening of resonances because of additional surface dephasing. All possible surface processes are taken into account, including the surface scattering, magnetic dipole and exchange interactions, etc.

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- (2) J.J. Berkhout and J.T.M. Walraven, Sticking and thermal accommodation of atomic hydrogen on liquid helium surfaces, in: Spin-Polarized Quantum Systems, ed. S. Stringari (World Scientific, Singapore, 1988, pp. 201 - 208).
- (3) N.P. Bigelow, J.M. Freed and D.M. Lee, Phys. Rev. Lett. **63** (1989), 1609.