Spin Supercurrent

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Abstract

We review the main properties of Spin Waves condensation to a coherent quantum state, named Homogeneously Precessing Domain (HPD). We describe the long range coherent transport of magnetization by Spin Supercurrent in antiferromagnetic superfluid $^3$He. This quantum phenomenon was discovered 20 years ago. Since then, many magnetic extensions of superconductivity and superfluidity have been observed: spin Josephson phenomena, spin current vortices, spin phase slippage, long distance magnetization transport by spin supercurrents, etc. Several new supercurrent phenomena have been discovered, like magnetically excited coherent quantum states, NMR in the molecular Landau field, spin-current turbulence, formation of stable non-topological solitons etc.

The projection of the spin of the Cooper pair on the direction of $\mathbf{d}$ is equal to zero, similar to the antiferromagnetic vector $\mathbf{l}$ in antiferromagnets.

In the case of a spatial gradient of $d_{\perp} = d_x + id_y$ the gradients of $\Psi_{\uparrow\uparrow}$ and $\Psi_{\downarrow\downarrow}$ have different signs. Its leads to counterflow of these two superfluids. This counterflow transports magnetization without mass transport and is called the spin supercurrent.

Spin supercurrents in superfluid $^3$He have been expected for a long time. The complexity of these phenomena follows from the fact that it is the coherent transport of a vector quantity, not a scalar one, as it is for mass and current charges in superfluidity and superconductivity. Consequently the general expression for the spin supercurrent has a tensor form and reads:

$$ J_{i\alpha} = \frac{\hbar}{2m} \rho_{i\alpha\beta} \Omega_{j\beta} $$

where $\rho_{i\alpha\beta}$ is the spin superfluid density tensor and $\Omega_{j\beta}$ are the phase gradients of the order parameter.

1. Introduction

Quantum spin dynamics and magnetization transport are presently of a wide interest both theoretically and experimentally. Here we consider the magnetically ordered system, where fundamental properties of spin quantum transport and spin waves condensation have been discovered, superfluid $^3$He. The superfluid $^3$He is a very interesting example of quantum liquid antiferromagnet. In contrast to ordinary magnetically ordered materials where we have spatial ordering that can be described by the language of sublattices, here we have a mixture of quantum liquids in different quantum states.

$$ \Psi(\mathbf{k}) = \Psi_{\uparrow\uparrow}(\mathbf{k}) | \uparrow\uparrow \rangle + \Psi_{\downarrow\downarrow}(\mathbf{k}) | \downarrow\downarrow \rangle + \sqrt{2} \Psi_{\uparrow\downarrow}(\mathbf{k}) | \uparrow\downarrow \rangle + | \uparrow\uparrow \rangle $$

where $\Psi_{\uparrow\uparrow}, \Psi_{\downarrow\downarrow}$ and $\Psi_{\uparrow\downarrow}$ are the amplitudes associated with the spin substates $| \uparrow\uparrow \rangle, | \downarrow\downarrow \rangle$ and $| \uparrow\downarrow \rangle$ respectively. The relation between these substates can be described by the vector $\mathbf{d}$ which is actually the axis of quantization of the Cooper pair state.

$$ \Psi(\mathbf{k}) = \begin{pmatrix} \Psi_{\uparrow\uparrow}(\mathbf{k}) \\ \Psi_{\downarrow\downarrow}(\mathbf{k}) \\ \Psi_{\uparrow\downarrow}(\mathbf{k}) \\ \Psi_{\downarrow\uparrow}(\mathbf{k}) \end{pmatrix} $$

$$ = \begin{pmatrix} -d_x(k) + id_y(k) \\ d_z(k) \\ d_x(k) \\ d_x(k) + id_y(k) \end{pmatrix} $$

2. Spin Waves condensation to a coherent state

The equations of NMR in $^3$He, so called Leggett equations, are similar to equations of antiferromagnetic resonance with an anisotropic term due to nuclear dipole-dipole interaction. The solution of this equations for bulk $^3$He-B shows that the magnetization precess on the larmor frequency if it is deflected less then magic dipole angle of 104°.
For bigger angles of deflection the additional positive frequency shift appears.

In the case of NMR in a gradient of magnetic field the gradient of \( d \) creates the spin supercurrent which transport the magnetization in the direction of higher magnetic field. Consequently the deflection of magnetization in the region of smaller magnetic field increases up to the value of 104°. At further deflection, the dipole dipole frequency shift compensate the gradient of magnetic field. The spatial magnetic energy potential became flat and spin waves condenses to a coherent state[1]. This state calls Homogeneously Precessing Domain (HPD), where the magnetization is deflected from the magnetic field and precesses coherently even in an inhomogeneous magnetic field.

The HPD is a new type of coherent states, the non-equilibrium, magnetically excited state. It can be explained[2] in full analogy to other coherent states in terms of ”off-diagonal long range ordering” ODLRO: the role of the particle number operator is played by a quasi-conserved quantity: the projection of magnetization \( M_z \) on the external magnetic field. The spin creation and annihilation operators \( M^\pm_z \) substitute the particle-nonconserving operators. The precession frequency \( \omega \) corresponds to the chemical potential, and the Zeeman energy \( E_Z = -\gamma HM_z \) corresponds to the particle energy \( nU \) in an external scalar potential. As a result the ODLRO in a spin system is given by

\[
< M^-_z > = \sqrt{M^2 - M^2_z} e^{i(\Phi + \omega t)}
\]  

It is important to note that the precession may be stable and coherent only if the following two conditions are satisfied:

(1) The internal energy \( E_D(M_z) \) (for \(^3\)He it is mainly the dipole-dipole interaction) is a concave function of \( M_z \) in the same way as the concave shape of the internal energy \( e(n) \) prevents the phase separation in liquid.

(2) The phase coherence is supported by the spin rigidity: the energy depends on the gradient of phase \( E_G = (K/2) (\nabla \Phi)^2 \), where the stiffness \( K \) plays the role of the superfluid density in mass superfluids. These conditions are satisfied for Larmor precession in superfluid \(^3\)He-B in which the dipole energy has the concave form and the magnetic stiffness is supported by the initial stiffness of the superfluid order parameter.

The coherent HPD state is metastable, for its creation it is necessarily to apply pulsed or CW NMR techniques. In the later case a small RF field compensates the small dissipation caused by the non-conservation of \( M_z \) due to the magnetic interaction with the normal component of \(^3\)He. The RF field frequency \( \omega \) plays the role of the chemical potential and serves as the Lagrange multiplier in the added term \( E_L = -\omega M_z \). The RF field frequency defines the equilibrium of the tipping angle of the precessing magnetization \( M_z = M \cos \lambda \) which should correspond to the resonance frequency \( \omega \):

\[
\omega - \gamma H = -\frac{\partial E_D}{\partial M_z}.
\]

In the same way the fixed chemical potential determines the equilibrium particle density.

3. Demonstration of spin supercurrent

In order to demonstrate the non-potential flow of magnetization, we have excited two HPD in two cylindrical cells by applying two independent RF fields. The cells were placed in the same magnetic field and connected by a channel of 0.6 mm diameter and 6 mm length. The HPD states play the role of electrodes, while the RF field frequency - the potential. In the magnetic field the spin current transports the Zeeman energy, which can be measured by the balance of dissipation in the two cells. We have demonstrated the spin current flows in agreement with the magnetization precession phase gradient along the channel. By adding an orifice inside the channel we were able to observe the Josephson phenomenon [3]. The description of many quantum spin dynamics effects can be found in the review article [4].

4. New results

The superfluid component of \(^3\)He magnetically interacts with the normal component, which is the source of magnetic relaxation. By cooling to very low temperatures, one can expect to observe a true persistent NMR precession, owing to a suppression of the normal component. Indeed, an unpredicted instability of precession was found at a temperatures below 0.4 \( T_c \) [5]. Now we can explain it as a new type of Suhl instability [6].

At the limit of extremely low temperatures of about 100 \( \mu K \), a truly near persistent signal of NMR precession was found [7]. It can ring for several hours at a frequency of 1 MHz! The theoretical and experimental investigations show, this signal is generated by a new coherent quantum state, a non-topological soliton [8]. This signal is sensitive to rotation, as was found in Helsinki [9]. Many other interesting phenomena related to spin waves condensation and spin supercurrent can be found in [4] and current publications.

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