Two-Fluid Theory for Spin Superfluidity in Magnetic Insulators

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Two-Fluid Theory for Spin Superfluidity in Magnetic Insulators,
Main Message

The two-fluid nature of the collective heat and spin transport in easy-plane magnetic insulators.

As an example that illustrates this physics, we discuss how the presence of a spin superfluid (whose density can be tuned by the magnetic field) leads to a reduction of the Spin Seebeck signal.
Below $T_c$ system as mixture of a normal fluid, viscous and carrying entropy and a superfluid one that propagates collectively and carries no thermal energy.

Experimentally verified model, e.g. fountain effect in Helium and thermoelectric effects in superconductors.

Origin of superfluidity resides in BEC.
Magnetic insulators

Spin-wave currents persist over longer distances

Free of Joule heating

Interconversion of magnetic and electric signal

Macroscopic quantum phenomena


Spin Seebeck effect

The Spin Seebeck effect is the direct conversion of a temperature gradient into a spin current.

\[ n_x \propto e^{-x/\lambda_n} \]


transport of out-of-equilibrium magnons characterized by the magnon diffusion length \( \lambda_n \)

Spin superfluid

\[ \mathcal{H} = \int d^3r \left( -\frac{A}{2s} \mathbf{s} \cdot \nabla^2 \mathbf{s} + B \hat{s}_z + \frac{K}{2s} \hat{s}_z^2 \right) \]

(Exchange) (Zeeman) (Easy-plane anisotropy)

At zero temperature

\[ \langle \hat{s}_z \rangle = -\frac{B}{K} = n_c - s \]

\[ \langle \hat{s}_- \rangle = \langle \hat{s}_x - i\hat{s}_y \rangle = \sqrt{2sn_c} e^{-i\phi} \]

Holstein-Primakoff (HP) transformation

\[ \hat{s}_z = \hat{\Psi}^{\dagger} \hat{\Psi} - s \]

\[ \hat{s}_- \simeq \sqrt{2s} \hat{\Psi} \]

Macroscopic BEC wavefunction

\[ \Phi \equiv \langle \hat{\Psi} \rangle = \sqrt{n_c} e^{-i\phi} \]

Superfluid velocity

\[ \mathbf{v}_c = -i \frac{\hbar}{2m|\Phi|^2} (\Phi^* \nabla \Phi - \Phi \nabla \Phi^*) = -\frac{\hbar}{m} \nabla \phi \]
The specific set up that we are proposing for an experimental device consists of an easy plane insulator sandwiched by two metal leads for injection and detection. Detection/injection through (inverse) Spin Hall effect.
Length-scales

\[ \lambda_{cx} \propto n_c^{-1/2} \]
condensate-cloud equilibration length

\[ \lambda_n \]
thermal magnon diffusion length

\[ n_x \propto e^{-x/\lambda_n} \]

Results

\[ j_x \propto \frac{1}{1 + \sqrt{1 + (\lambda_n/\lambda_{cx})^2}} \]

Experimentally, the density of the thermal cloud can be controlled by the ambient temperature. The relative density of the condensate and the thermal cloud can be tuned by the application of the magnetic field. At large fields, when the order parameter is normal to the easy plane, the condensate density is zero. Below the Curie temperature, sweeping the magnetic field cuts across the phase transition between the condensate and the normal phase. Approaching from the normal side, the appearance of the condensate below the phase transition point leads to a new spin transport regime.
Conveyer-belt physics

On the other side, the process reverses—the negative chemical potential induces evaporation closing the conveyer belt.
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Thank you for your attention!