The Influence of Superflow on Collective Excitations in $^3$He-B

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The influence of superflow on the order parameter collective modes in $^3$He-B is investigated for temperatures $0 \leq T/T_c \leq 0.5$ by the continual integral method. The superflow induces a gap distortion, which splits the pair-breaking, squashing, and real squashing modes at zero momentum $k$. Furthermore, a crossing of the real squashing mode branches with different $|J_z|$ occurs at nonzero $k$. In addition, the superflow makes it possible to observe the pair-breaking modes and causes a hydrodynamic shift of longitudinal NMR frequency.

1. INTRODUCTION

Brusov and Popov investigated the influence of gap distortion caused by dipole interaction or magnetic or electric fields on order parameter collective excitations in $^3$He-B. However, there is at least one other cause of a similar gap distortion, namely the presence of superflow. As Vollhardt and Maki pointed out, the practical reason for studying the effects of a uniform current on the properties of superfluid $^3$He is that even a small temperature gradient introduces an appreciable superflow in liquid $^3$He.

The superflow leads to several important consequences. For example, it causes hydrodynamic shifts of NMR frequencies in both A and B phases and other changes in the NMR absorption through orienting effects on order parameter degrees of freedom.

The dispersion-induced splitting of the real squashing mode (rsq) in the B phase, which was predicted by Brusov and Popov and which was observed by Shivaram et al., is associated with the presence of superflow. The coupling of zero sound with the rsq mode (at least with the branches of the rsq mode with $J_z = \pm 1, \pm 2$) takes place via the superflow.

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Kleinert\(^9\) has shown that the squashing (sq) and rsq modes in the B phase each split into sets of three branches for \(T = T_c\) because of the superflow.

In this paper I investigate the influence of uniform superflow on the order parameter collective excitations in \(^3\)He-B in the temperature region \(0 \leq T \leq T_c/2\). I shall show that the superflow-induced gap distortion splits the pair-breaking (pb), sq, and rsq modes at zero momentum \(k\). Furthermore, a crossing of the rsq mode branches with different \(|J_z|\) appears at nonzero \(k\). The superflow makes it possible to observe the pb modes and causes a hydrodynamic shift of the longitudinal NMR frequency.

2. THE INFLUENCE OF SUPERFLOW ON THE ORDER PARAMETER

The order parameter of \(^3\)He-B is proportional to the matrix \(R_y(\hat{n}, \theta_0)\) that rotates the spin space with respect to the orbital space,

\[
A_{ij} = \Delta(T) R_{y ij} (\hat{n}, \theta_0) e^{i\theta}
\]

(1)

The energy gap \(\Delta(T)\) is isotropic; the rotation axis \(\hat{n}\) and rotation angle \(\theta_0\) are arbitrary in the absence of dipole interaction and external perturbations.

The dipole interaction

\[
F_D = g_D (A_{ij} A_{ji}^\ast - A_{ij} A_{ji}^\ast - \frac{2}{3} A_{ij} A_{ji}^\ast)
\]

(2)

fixes the rotation angle \(\theta_0\) at \(\cos^{-1} (-1/4)\), but the axis \(\hat{n}\) remains arbitrary.

The superflow with energy\(^10\)

\[
F_{\text{flow}} = (\frac{1}{2} \rho_s / |\Delta|^2) (v_{sr} A_{ij}^\ast v_{st} A_{ij})
\]

(3)

couples only to orbital coordinates and (3) is independent of the direction \(\hat{n}\). However, there is a small distortion of \(A_{ij}\) related to the so-called depairing effect, of order of the ratio of perturbation energy \(\frac{1}{2} \rho_s v_s^2\) to condensation energy \(F_{\text{cond}}\). Through this distortion of the order parameter the superfluid energy\(^10,11\)

\[
F_{\text{flow}} = -a(\hat{n} v_s)
\]

(4)

fixes \(\hat{n} || v_s\). This situation is similar to the orienting effect of a magnetic field.\(^10-12\)

Besides this orienting effect on the \(\hat{n}\) vector, this distortion of \(A_{ij}\) leads\(^10\) to different values of the energy gap parallel (\(\Delta_{||}\)) and perpendicular (\(\Delta_{\perp}\)) to the superflow \(v_s\).

We take both these facts into account, the orienting effect of the superflow (\(\hat{n} || v_s\)) and the gap distortion (\(\Delta_{||} \neq \Delta_{\perp}\)) caused by the superflow. We choose the angle \(\theta_0 = 0\) for simplicity.