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Faraday Effect for Transverse Waves in Superfluid ^{3}He-B

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Low-frequency ($\omega \ll \Delta(T)$) transverse sound in superfluid ^{3}He becomes overdamped at temperatures near T_c. However, at low temperatures ($T \lesssim 0.3\ T_c$) the off-resonant coupling to the $J = 2^-$, $M = \pm 1$ modes stabilizes a propagating transverse current mode with a large phase velocity and low damping for frequencies above that of the $J = 2^-$ mode. A magnetic field with $\vec{H} || \vec{q}$ lifts the degeneracy of right- and left-circularly polarized waves giving rise to the analog of circular dichroism and birefringence of electromagnetic waves. These features suggest that transverse waves may be more easily detected in the B-phase than in normal ^{3}He. Below we give a brief summary of results on transverse waves in ^{3}He-B [1].

Many predictions of Landau's theory of a normal Fermi liquid have been confirmed by experiments on the low-temperature phases of ^{3}He (*c.f.* Baym and Pethick [2]). Most notable is the prediction of a the collisionless longitudinal 'zero' sound mode. Landau also pointed out the possibility of a collisionless transverse sound mode, *i.e.* a propagating shear wave [3]. While the experimental confirmation of longitudinal zero sound is a well known achievement [4], the evidence for transverse sound in ^{3}He is much less clear [5]. We argue that a propagating transverse current mode may be more easily detected at very low temperatures in the B-phase of superfluid ^{3}He.

Earlier investigations of low-frequency transverse sound concluded that the mode would disappear just below T_c [6,7,8]. Maki and Ebisawa [9] examined the coupling of transverse currents to the $J = 2^-$ modes. Their numerical calculations for frequencies below the $J = 2^-$ mode, $\omega < \omega_{2-}(0) \simeq \sqrt{12/5}\Delta_0$, show a purely reactive response at low temperatures, *i.e.* non-propagating solutions. We show that transverse waves do propagate at higher frequencies.

There are two important differences between low-frequency, collisionless ($1/\tau \ll \omega \ll \Delta(T)$) longitudinal and transverse sound modes in superfluid ^{3}He. First, transverse sound does not couple to density fluctuations, for which there is a very strong restoring force. The weaker quasiparticle contribution to the restoring force for transverse current dies out as the gap develops below T_c. Furthermore, the phase mode, which has a phonon-like dispersion relation and is responsible for longitudinal sound at low temperatures ($T \ll T_c$), does not couple to transverse currents. In short, the transverse modes do not propagate at low frequencies because they do not couple to the phase mode, nor to any other propagating mode.

At high frequencies, $\omega \sim \Delta$, current fluctuations couple to other collective modes of the order parameter. In ^{3}He-B the $J = 2^-$, $M = \pm 1$ modes couple strongly to right- and left-circularly polarized transverse currents, and for frequencies $\omega_{2-}(0) < \omega < 2\Delta_o$ these transverse modes propagate with low attenuation at low temperatures, $T \lesssim 0.3\, T_c$ [1]. Figure 1 shows the real part of complex phase velocity as a function of temperature. Note that $\mathrm{Re}C \geq v_f$ for $\omega > \omega_{2-}(0)$ and $T \ll T_c$. In this temperature range the attenuation from thermally excited quasiparticles is suppressed.

Right- and left circularly polarized transverse modes, which are degenerate in zero field, propagate with different complex phase velocities in a magnetic field, $\vec{H} || \vec{q}$. In Fig. 2 we show the splitting of the phase velocity vs. T/T_c for $\gamma H/2\pi = 2\,MHz$. A longitudinal magnetic field breaks time-reversal symmetry by producing a Zeeman splitting of the $J = 2^-$ modes; this Zeeman effect leads to the splitting in the phase velocity for RCP and LCP waves. For linearly polarized waves at low temperatures a Faraday effect should be observable. The rotation of the polarization direction has a spatial period that can is easily made to be comparable to or smaller than typical path lengths. For $T \ll T_c$, $\omega_L/2\pi = 1.3$ MHz ($H \sim 220$ G) and $C \sim v_f \simeq 32$ m/s, the

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wavelength for a 2π rotation of the polarization is $\lambda_H \simeq 0.25$ mm.

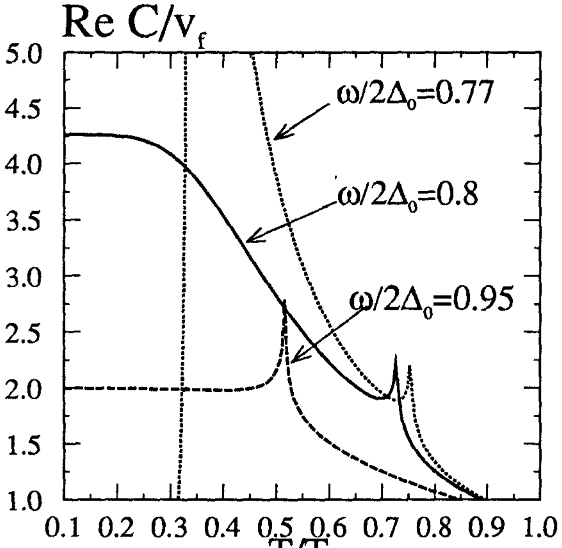

Fig. 1 Real part of the phase velocity for transverse waves with $F_1^s = 15$ and $F_2^s = 0$. At low temperatures transverse waves propagate with a phase velocity $Re\ C > v_f$ for frequencies $0.77 \lesssim \frac{\omega}{2\Delta_0} < 1$.

Thus, orthogonal polarization transducers could be used to excite and detect linearly polarized transverse waves by adjusting the field so that the path length is $d = (2n+1)\lambda_H/4$. Such a signal would be direct evidence for the propagation of transverse currents via the $J = 2^-$, $M = \pm 1$ order parameter modes.

Finally, we note that our results correspond to the response of *bulk* ^{3}He-B to a probe of transverse excitations. In the high attenuation regime, where the transverse current decays rapidly with distance from the moving surface, the acoustic impedance is likely to have substantial contributions from surface effects not included in any present theory. However, in the low attenuation regime transverse current will propagate and the predicted frequency and temperature dependences of the phase and group velocities should be observable. Nevertheless, there may be additional channels for coupling of transverse momentum from the vibrating surface to liquid ^{3}He.

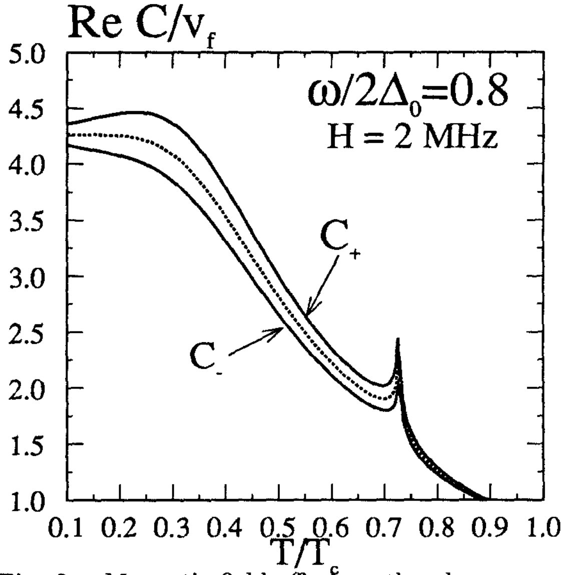

Fig. 2 Magnetic field effect on the phase velocity of RCP and LCP polarized waves. The real part of $C_\pm(\omega, T)$ for transverse waves are shown for a field of $\gamma H/2\pi \simeq 2$ MHz. We have chosen a large field to emphasize the splitting.

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