Observation of an Evolving Standing-Wave Pattern Involving a Transverse Disturbance in Superfluid ^{3}He-B

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We have observed a series of oscillations in the transverse acoustic response of superfluid ^{3}He-B, which, in analogy with earlier observations involving longitudinal sound, suggest an evolving standing-wave pattern. These oscillations were observed with 60.8 MHz transverse sound at pressures between 1 and 3 bars. The change in the reciprocal of the phase velocity can be obtained from these data, and it is compared with a recent theoretical prediction [G. F. Moores and J. A. Sauls, J. Low Temp. Phys. **91**, 13 (1993)].

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Experimental studies of the propagation of transverse zero sound in both the normal fluid and superfluid phases of ^{3}He have been problematic, due to several factors. Since transverse zero sound arises from a very small distortion of the leading edge of the Fermi surface of ^{3}He, it travels only slightly faster than the Fermi velocity. This gives rise to a large attenuation of this collective mode. In addition, quasiparticles excited by a driven transducer (also traveling near the Fermi velocity) can contribute to any signal received by a second transducer, masking (to some extent) the collective mode signal. This point was stressed by Flowers, Richardson, and Williamson [1] in their analysis of the normal fluid data of Roach and Ketterson [2].

Recently, Moores and Sauls [3] have shown that in the B phase of superfluid ^{3}He the liquid can support a propagating transverse current via the coupling to the $J=2^-$, $J_z=\pm 1$ collective modes. The effect of this collective mode, the so-called squashing (Sq) mode, is to provide a contribution to the molecular field which stabilizes the propagation of transverse current waves. The interval for which this collective mode can support a propagating mode is $2\Delta(T,P)>\hbar\omega>(12/5)^{1/2}\Delta(T,P)$, where ω is the acoustic frequency, the energy $2\Delta(T,P)$ corresponds to the threshold for pair breaking, and $(12/5)^{1/2}\times\Delta(T,P)/\hbar$ is the frequency of the Sq mode. A restriction on this prediction is that the quasiparticle damping not be too high; Moores and Sauls estimate this damping to be low enough to allow propagation for $T\lesssim 0.3T_c$. A qualitative understanding of the results of this model may be gained by considering the dispersion relation obtained in a long wavelength approximation ($qv_f\ll\omega$) and neglecting F_2^s (Eq. 54 of Ref. [3]):

$$\left(\frac{\omega}{qv_F}\right)^2=\frac{F_1^s}{15}[1-\lambda(\omega;T)]+\frac{2}{75}F_1^s\lambda(\omega;T)\times\frac{\omega^2}{(\omega+i\Gamma)^2-\frac{12}{5}\Delta^2-\frac{2}{5}q^2v_F^2}\,. \quad (1)$$

Here $q=k+i\alpha$ is the complex wave vector ($k=\omega/c$, where c is the phase velocity, and α is the attenuation), Γ is a phenomenological linewidth for the Sq mode (which is discussed in further detail below), and $\lambda(\omega;T)$ is the weak coupling Tsuneto function (discussed in detail in the appendix of Ref. [3]). In this equation the resonant coupling to the Sq mode is clearly seen. For an overview of the properties of superfluid ^{3}He we refer the reader to recent reviews [4].

The data to be presented here consist of a series of oscillations in the acoustic response of a loaded quartz transducer (the load in this case being superfluid ^{3}He). The interpretation of these oscillations is similar to that used earlier in the study of longitudinal sound in superfluid ^{3}He [5]. In the present case an acoustic transducer was positioned a short distance from a flat surface which acted as an acoustic reflector. When the attenuation is low enough that a returning signal from the reflector is large enough to make an observable shift in the transducer response, the evolution of a standing wave pattern can be observed. The total phase shift is given by

$$\phi=kD=2\pi n+\phi_0\,, \quad (2)$$

where n is the number of wavelengths along the total sound path, k is the wave vector of the mode, D is the total (or round trip) distance the sound travels, and ϕ_0 is a fixed but unknown phase shift. If the wave vector of the mode changes, then the round trip phase will also change; if the wave vector is continuously swept, via its temperature or pressure dependence, more wavelengths are added to (or removed from) the standing wave pattern, causing the acoustic response to oscillate. The change in the inverse of the phase velocity may be related to the number of oscillations through a simple manipulation of Eq. (2):

$$n(T,P)=2df\left(\frac{1}{c(T_0,P_0)}-\frac{1}{c(T,P)}\right), \quad (3)$$

where $n(T,P)$ is the number of oscillations between (T_0,P_0) and (T,P), f is the excitation frequency of the transducer, and d ($=D/2$) is the separation between the transducer and reflector.

The acoustic cell and the spectrometers, as well as the

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cryogenic techniques, were identical to those described previously [6], and will only briefly be outlined here. The acoustic cell consisted of two separate single-ended acoustic cavities, each excited by its own frequency modulated, continuous wave, superheterodyne spectrometer. One cavity utilized an ac cut quartz transducer, tuned to 60.8 MHz, to probe the transverse response. It was modulated at 1 kHz and had a nominal room temperature one way sound path of 30.5 μm. The other cavity utilized an x cut quartz transducer, tuned to 61.4 MHz, to probe the longitudinal response. It was modulated at 400 Hz and its nominal room temperature one way sound path was 12.5 μm; the path length at He temperatures was deduced to be 23.6 μm by comparing the spacing of adjacent oscillations (observed while depressurizing the cell in the normal fluid) against previously measured values of the pressure dependence of the longitudinal zero sound phase velocity [7].

The ^{3}He sample was cooled by adiabatic nuclear demagnetization of copper. The temperature was measured by monitoring the magnetic response of a lanthanum cerium magnesium nitrate (LCMN) thermometer which was calibrated against the T_c signatures in the acoustic response. The pressure dependence of T_c was taken from Greywall [8]. The details of the calibration technique are similar to those described in Ref. [6], with two significant improvements. First, we utilized an LCMN tower mounted on top of the acoustic cell, which was approximately 50% closer to the acoustic cell than in the previous work. This tower also contained more LCMN powder, giving better temperature resolution. Second, we obtained sufficient calibration points to perform separate calibrations for demagnetization (cooling) sweeps and magnetization (warming) sweeps. The rms scatter of the respective T_c's from these calibrations was 15.7 μK for the cooling calibration and 9.3 μK for the warming calibration.

The data were taken by sweeping the temperature at a fixed pressure and simultaneously monitoring the response of the LCMN thermometer and both the transverse and longitudinal spectrometers. A typical trace of the transverse response is shown in Fig. 1. The position of the transition temperature (T_c), pair breaking edge (PB), and squashing mode signatures obtained from the corresponding longitudinal response are indicated on this trace. The region between the pair breaking edge and Sq mode is expanded in Fig. 1(b), where we clearly see an oscillatory response indicative of an evolving standing wave pattern. These oscillations in the transverse response were only observed in the temperature region between the pair breaking edge and the squashing mode. We also observed oscillations in the longitudinal response, but with two notable differences from the transverse oscillations: (i) the ratio of the number of transverse oscillations to longitudinal oscillations was (roughly) between 3 to 1 and 15 to 1, depending on the temperature region,

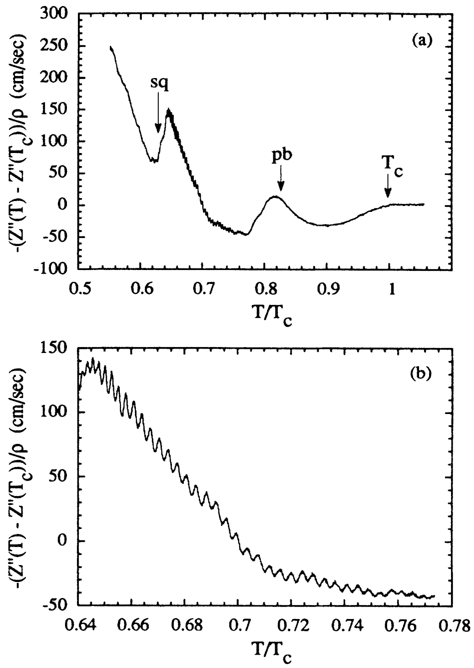

FIG. 1. The transverse acoustic response at 2.11 bars and 60.8 MHz. The vertical axis is the change in the imaginary component of the acoustic impedance with respect to that at T_c; details of the spectrometer calibration are described in Ref. [6]. The T_c, pair breaking (PB), and squashing mode (Sq) labels in (a) are based on the position of these features in the longitudinal sound trace observed simultaneously. The region between the pair breaking edge and Sq mode in (a) is expanded in (b).

and (ii) the oscillations in the longitudinal response were observed on both sides of the squashing mode, whereas the transverse response exhibited these oscillations only on the high temperature side of the Sq mode [$\omega > (12/5)^{1/2}\Delta/\hbar$]. The highest pressure at which we observed these oscillations in the transverse response was 3.05 bars (next highest pressure studied was 3.5 bars, and no oscillations were observed). The lowest pressure at which we observed these oscillations was 1.05 bars. Below that pressure we could not cool below the pair breaking edge (at 60.8 MHz).

In any experiment involving a transverse sound transducer one must be concerned with the possibility of producing a small admixture of longitudinal sound (in addition to the transverse sound). However, based on the differences between the period of the oscillations observed with the transverse and longitudinal transducers, as well as a careful consideration of the geometry of the acoustic cell, we have concluded that there is no measurable longitudinal component in the observed signal (in the temperature region where these oscillations occurred).

The temperature spacing between adjacent oscillations in the transverse response became smaller at lower temperatures, indicating that the phase velocity was changing more rapidly at lower temperatures. In analogy with longitudinal sound, this is consistent with a level repulsion at the crossing between the sound mode and the Sq mode. We may utilize Eq. (3) to graphically represent the temperature dependence of the phase velocity, but to do so requires a knowledge of the phase velocity at one reference point. To obtain such a reference point we appealed to the theoretical model of Moores and Sauls, utilizing Eq. (1). The position of the Sq mode resonance involves corrections due to a nonzero value of F_2^s and an f-wave pairing amplitude [9], as well as any strong coupling effects. However, since the present experiment reports a new phenomena (i.e., the velocity of a propagating transverse disturbance in the vicinity of the Sq mode), and is not intended to be a high precision measurement of the Sq mode itself, we have chosen to normalize the Sq mode resonance (for each pressure studied) to the temperature at which the Sq mode signature was observed (simultaneously) with longitudinal sound. In this manner the Sq mode frequency used in these calculations was given by

$$\hbar^2\omega_{\mathrm{Sq}}^2 = a_{\mathrm{Sq}}\Delta_{\mathrm{BCS}}^2(T,P)\,, \tag{4}$$

where

$$a_{\mathrm{Sq}} = \frac{\hbar^2\omega_{\mathrm{sound}}^2}{\Delta_{\mathrm{BCS}}^2(T_{\mathrm{Sq}},P)}\left[1-\frac{7}{15}\left(\frac{v_F}{c_0}\right)^2\right]. \tag{5}$$

Here $\Delta_{\mathrm{BCS}}(T_{\mathrm{Sq}},P)$ is the magnitude of the BCS gap for the temperature at which the Sq mode signature was actually observed in the longitudinal sound trace for the pressure P, and c_0 is the longitudinal zero sound velocity. The term in Eq. (5) involving v_F/c_0 accounts for the dispersion correction to the Sq mode resonance for $J_z=0$, which is the component that couples to longitudinal sound in zero magnetic field; the dispersion for the $J_z=\pm 1$ components is included in Eq. (1). The values of $a_{\mathrm{Sq}}/(12/5)$ were between 1.006 and 1.096 [10].

In Fig. 2 we have plotted the phase velocity information contained in the observed standing wave oscillations against the prediction obtained from Eq. (1). We remind the reader that this equation represents the long wavelength ($qv_f \ll \omega$) approximation of the Moores-Sauls calculations. The short wavelength corrections, as indicated in Fig. 4 of Ref. [3], appear to cause a more rapid increase in the phase velocity from its value at the pair breaking edge, which might account for some of the discrepancy seen in Fig. 2(a). These short wavelength corrections, while nontrivial, do not have a large effect on either the order of magnitude or the shape of the velocity versus temperature curve. While the use of the long wavelength approximation may not be strictly justified for the present data set, we have adopted it to obtain a qualitative comparison between experiment and theory.

The same calculation which is reflected in Fig. 2 also yielded predictions for the round trip attenuation for our experiment: between 52 and 94 db at 2.82 bars, and between 32 and 45 db at 2.11 bars. Although the amplitude of the observed oscillations was quite small (indicating a large attenuation regime), these predicted values are approximately 25%–50% larger than what we would expect to be observable [11]. The calculation of the attenuation was sensitive to the choice of the Sq mode lifetime, τ_{Sq}, which enters Eq. (1) through the linewidth Γ. The form of τ_{Sq} was taken from Einzel [12], which was scaled by the quasiparticle lifetime at T_c. The value of this lifetime was estimated by extrapolating the value obtained from Sq mode data taken at 14 bars [13], using the same pressure dependence as the quasiparticle lifetime obtained from viscosity measurements [14]. The inexact nature of these estimates could easily account for the discrepancy in the attenuation calculations. We should point out that by comparing the relative amplitude of the observed oscillations at different pressures it was apparent that the attenuation decreased as the pressure decreased, which is in agreement with the theoretical predictions. Conversely, this would indicate that as the pressure is increased the attenuation would reach a level at which the sound waves are too highly attenuated to produce a measurable returning signal at the transducer, at which point no standing wave behavior would be observed. This regime ap-

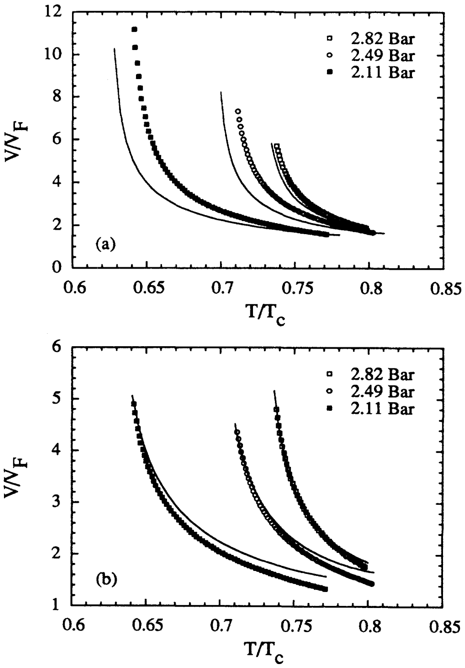

FIG. 2. The transverse phase velocity (normalized to the Fermi velocity) for the pressures indicated, based on Eq. (3). The symbols in this figure represent the position of successive maxima and minima of the standing wave oscillations (i.e., every half oscillation). The solid lines represent the theoretical prediction of Moores and Sauls in a low q approximation (see Ref. [3]), based on Eq. (1). In (a) the experimental data are normalized to this prediction at the highest temperature shown, and in (b) the normalization is done at the lowest temperature shown. All data points were taken at 60.8 MHz.

peared to occur between 3 and 3.5 bars for the sound path employed in our experiments.

The above results may be summed up as follows. The observed oscillations in the transverse acoustic response appear to be a manifestation of an evolving standing wave pattern associated with a propagating transverse disturbance. Such a phenomena would be insensitive to the effects of quasiparticle transmission (traveling at essentially the Fermi velocity, which is independent of temperature), and hence is strong evidence for the existence of a propagating transverse mode. Our observations agree with the following predictions of Moores and Sauls: (i) propagation occurs only between the pair breaking edge and the Sq mode and (ii) the predicted phase velocity change and round trip attenuation are of the same order of magnitude as those which are inferred from our data. While our data set was taken at T/T_c values for which Moores and Sauls expect the quasiparticle damping to be prohibitively large, we have been able to probe an unusually large attenuation regime through the utilization of an extremely short sound path.

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