Measurements of the transverse acoustic impedance of superfluid ^{3}He-B

S. Kalbfeld, D. M. Kucera, and J. B. Ketterson
Department of Physics and Astronomy, Northwestern University, Evanston, Illinois 60208
(Received 13 April 1993)

The transverse acoustic impedance in the B phase of superfluid ^{3}He has been measured using a cw technique. These measurements were performed over a pressure range of 4.4–20.9 bar and at a frequency of 61 MHz. A simultaneous measurement of the longitudinal response at 61 MHz was made on a separate sound path. The availability of both probes allows a direct comparison of the transverse response with known features in the longitudinal response.

One of the most startling predictions of Landau's Fermi-liquid theory was the possibility of a propagating transverse sound mode. Strong evidence for the existence of transverse zero sound was first obtained by Roach and Ketterson,[1] both through propagation measurements and acoustic impedance measurements. Further acoustic impedance studies were performed by other groups.[2,3] However, obtaining quantitative information about transverse zero sound from these results has proven difficult. Since transverse zero sound would travel only slightly faster than the Fermi velocity, it would be highly attenuated, and single-particle excitations could mask its effect in transmission experiments, as well as contribute to the acoustic impedance, as was pointed out by Flowers, Richardson, and Williamson.[4]

For transverse sound in superfluid ^{3}He the analysis is more complicated. However, since ^{3}He is the only substance for which unconventional BCS superfluid behavior has been clearly established, it serves as a model system and hence should be subjected to a variety of probes; this work communicates new results on the acoustic shear response. Early theoretical work by Combescot and Combescot[5] and Maki and Ebisawa[6] showed that the Fermi-liquid mean field which supported transverse zero sound in the normal fluid would fall off in the superfluid. A more complete study was done by Einzel *et al.*,[7] but in none of these cases were the effects of pair breaking (PB) and/or order parameter collective modes (OPCM's) taken into account. Aside from the present work, the pulsed acoustic impedance measurement of Roach and Ketterson[8] has been the only experimental work done in superfluid ^{3}He using transverse sound. The results of this earlier work were for a limited range of temperature and pressure, and, although a marked change in the transverse acoustic impedance was observed at temperatures below the superfluid transition, this behavior could not be correlated with the effects of PB or OPCM.

The interest in transverse sound in superfluid ^{3}He has been renewed by the recent work of Moores and Sauls.[9] They have found that the existence of the $J=2^-$ OPCM [referred to as the squashing (sq) mode] can provide an additional mechanism for supporting a transverse response.

The OPCM's have been intensively studied using (longitudinal) ultrasound, as reflected in recent reviews.[10,11] In the present work we have attempted to use this extensive knowledge of the sq mode behavior as a standard against which we may study transverse sound. We have attempted to not only extend the previous work of Roach and Ketterson, but to make the important direct comparison of the transverse acoustic impedance against the already well-understood longitudinal acoustic impedance in superfluid ^{3}He.

Because of the high attenuation associated with transverse zero sound, propagation (or transmission) studies would require a rather short sound path length. In the normal fluid this path length is likely to be of the same order as the quasiparticle mean free path. An alternative to a propagation experiment is an acoustic impedance experiment. To make simultaneous measurements of the transverse and longitudinal acoustic impedances we constructed a cell consisting of two separate acoustic cavities: one with an x-cut quartz transducer (probing the longitudinal response) with a (nominal) 20-MHz fundamental frequency and the other with an ac-cut quartz transducer (probing the transverse response) with a (nominal) 12-MHz fundamental frequency. The transducers where placed on opposite sides of a flat, solid reflector,[12] with the sound paths sandwiched between this reflector and each transducer. The sound path for the longitudinal transducer was defined by a gold-plated tungsten wire with a nominal diameter of 12.5 μm and the sound path for the transverse transducer was defined by a similar wire with a nominal diameter of 30.5 μm. The fifth harmonic of the transverse transducer was 60.77 MHz and the third harmonic of the longitudinal transducer was 61.36 MHz. Each transducer was connected to its own rf spectrometer. The measurements reported here are a completion of the preliminary results which we recently reported,[13] and we refer the reader to this reference for further details of the experimental setup.

The measurements for each spectrometer were taken using a single-ended, frequency-modulated (FM), continuous-wave acoustic impedance technique. The details of this type of spectrometer have been described elsewhere.[13,14] Both the longitudinal and transverse spectrometers were essentially identical except that the former was modulated at 400 Hz and the latter at 1 KHz, to avoid any possibility of mutual interaction. While still in the normal fluid region, the transducer response was calibrated by shifting the frequency of its associated oscillator by a known amount from the nominal transducer res-

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onant frequency (which is equivalent in magnitude, but opposite in sign, to a shift in the transducer resonance relative to the excitation frequency) and noting the corresponding change in the level of the first harmonic of the amplitude-modulated (AM) response of the transducer (as detected using a superheterodyne AM receiver followed by a lock-in amplifier). If we were initially tuned to the transducer resonance, then by relating the lock-in response to a shift in the resonant frequency of the transducer we could (in regions of very high attenuation) measure changes in the imaginary component of the acoustic impedance through the relation[1,15]

$$\frac{\Delta f}{f_0}=\frac{2Z''}{\pi R_Q}\ , \tag{1}$$

where $Z=Z'+iZ''$ is the complex acoustic impedance of the liquid, f_0 is the fundamental frequency of the transducer, and R_Q is the acoustic impedance of the quartz transducer (assumed to be real).

The acoustic cell was mounted on a copper nuclear demagnetization cryostat, as described in earlier work.[14] The pressure was measured by a Paro Scientific pressure gauge situated at room temperature, and a capacitance-type pressure gauge mounted on the nuclear-stage heat exchanger and calibrated with the former. The temperature was measured with a Lanthanum Cerium Magnesium Nitrate (LCMN) thermometer[16] mounted on the nuclear-stage heat exchanger, but about 10 cm away from the actual position of the acoustic cell. The LCMN magnetic response was calibrated against the T_c signatures in the longitudinal wave spectrometer; the pressure dependence of T_c was taken from Greywalls work.[17] It was found that all of the calibration points taken while cooling fell to one side of a best-fit line to a Curie-Weiss-type law while those taken while warming fell to the other side of this line.[18] The deviation from this best-fit line was proportional to the cooling (warming) rate, i.e., there was a thermal lag between the LCMN thermometer and the acoustic cell. An estimation of the thermal response time between the LCMN thermometer and the sound path, based on the geometry of the sound cell and the temperature and pressure range studied, was 3–8 min. Since the sound signatures of interest generally occurred approximately 35–50 min after the beginning of each temperature sweep, we could safely conclude that the system was in a thermally steady state which reflected a thermal gradient of the form

$$T_{\text{sound}}=T_{\text{LCMN}}+\alpha(P)\bar{\dot{T}}+\gamma(P)\ . \tag{2}$$

The cooling (warming) rate, $\dot{T}$, which accounted for the steady-state thermal gradient, was obtained from the LCMN response, χ, and its time derivative, $\dot{\chi}$; $\gamma(P)$ represented the effects of external heat leaks. Both $\alpha(P)$ and $\gamma(P)$ were taken as first-order polynomials (in the pressure) whose coefficients were represented as additional fit parameters. When a least-squares fit to a Curie-Weiss-type law [which included the corrections embodied in Eq. (2)] was performed, the average deviation of the calibration points from this fit was $\pm 21\ \mu$K, which was within the error bars associated with the calibration points. The LCMN was used to measure differences in temperature with respect to well-understood features in the longitudinal spectrometer traces, viz. T_c or the sq mode, so that in actuality the last two terms in Eq. (2) cancel out.

The data were taken in the following manner: while still in the normal fluid (i.e., a region of relatively constant acoustic impedance), each transducer was tuned to its respective resonance (about 61 MHz) and calibrated as outlined above. The temperature was then swept (at a constant cell pressure) and the response of both spectrometers, as well as the LCMN thermometer, were monitored. In all cases, the response of both spectrometers observed on cooling sweeps was reproduced on the subsequent warming sweep, as well as upon any repeated cooling and warming sweeps. The cooling sweeps at 15.6 and 4.4 bars were performed first with both spectrometers connected to their respective transducers and then with only the transverse spectrometer connected; at both pressures the transverse response was unaffected by the presence of the longitudinal spectrometer, ruling out any possibility of crosstalk between the two spectrometers. A comparison of the responses of the two spectrometers reveals that they differ significantly, and in particular we do not appear to observe any significant longitudinal response with the transverse transducer.

Figure 1 shows raw data traces of both the longitudinal and transverse spectrometers. In the longitudinal traces at lower pressures, the oscillations at temperatures below the pair breaking edge are caused by changes in the standing wave pattern due to the changing phase velocity near the sq mode. The sq mode is observed as the narrow region in the middle of these oscillations where their amplitude decayed to zero (due to the high attenuation in the region of this mode). At each pressure studied the most prominent feature in the transverse sound is the sudden drop in the imaginary acoustic impedance at a temperature somewhat below T_c. With the exception of the data taken at 4.4 bars, there was no signature at the superfluid transition itself. A similar response (of comparable magnitude but reported with the opposite sign) was noted by Roach and Ketterson[8] using a pulsed technique. In the present work this "edge" was always approximate-

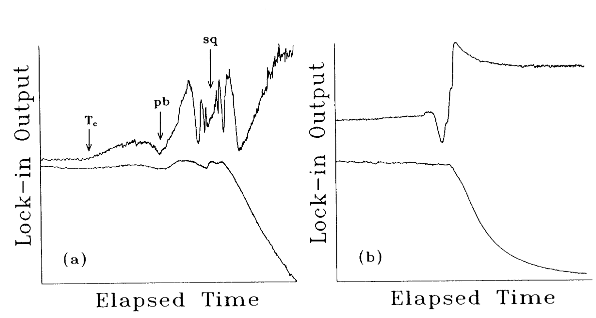

FIG. 1. Raw data traces at pressures of (a) 4.4 bars, and (b) 15.6 bars. The upper trace in each case is the longitudinal response. Trace (a) is for a cooling sweep and (b) is for a warming sweep. The arrows in (a) denote the T_c, pair breaking (pb), and squashing mode (sq) signatures in the longitudinal acoustic impedance.

ly coincident with the passage of the sq mode in the longitudinal spectrometer, a correlation which was not possible in the earlier work.

We do not expect the coupling to the $J=2^-$ manifold for the transverse and longitudinal spectrometers to exactly coincide because of (i) the slight difference in transducer frequencies, and (ii) the different dispersion for each wave; furthermore, on symmetry grounds the transverse sound should couple to the $J_z=\pm1$ modes[9] while longitudinal sound couples to the $J_z=0$ mode (for $H=0$). (To calculate the temperature separation between the two cases one would have to know the sound velocity for transverse sound in the temperature and pressure region of the collective mode, where it may differ significantly from the Fermi velocity.) The close correlation between the sq mode (as observed with longitudinal sound) and the observed signature in the transverse response implies that if this signature is due to an interaction of a traveling transverse wave with the sq mode, then the wave vector of this is much smaller than that of a wave traveling only slightly faster than the Fermi velocity. Figure 2 shows representative traces of the imaginary transverse acoustic impedance, with the position of the sq mode, as it was simultaneously observed in the longitudinal acoustic impedance response, marked by the arrow in each trace. The scale on each set of axes has been set the same to emphasize the evolution of the transverse acoustic impedance over a wide pressure range.

In addition, we point out some less prominent structure in the transverse acoustic impedance response, which is seen on either side of the arrows in Fig. 2. Although these features were seen at all pressures, they became more prominent at lower pressures. In Fig. 3 we have enlarged the traces in Figs. 2(a) and 2(d) (4.4 and 10.5 bars, respectively) to emphasize the evolution of these features as the pressure was lowered. At temperatures above the sq mode these features might be interpreted as due to a standing wave pattern. Based on this assumption, we could obtain the change in the phase ve-

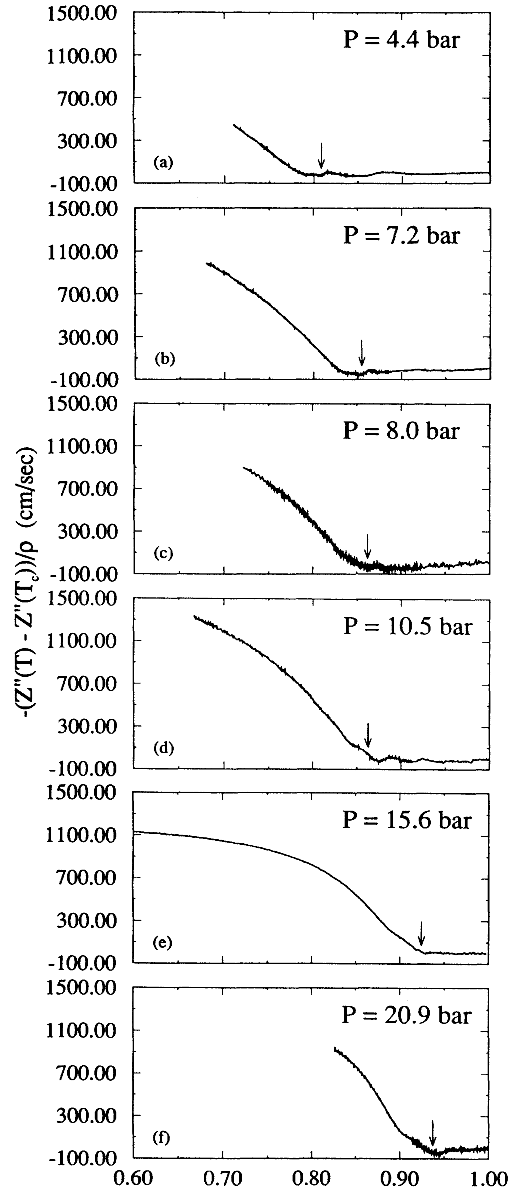

FIG. 2. Imaginary transverse acoustic impedance (measured as a change with respect to that at the transition temperature) for the pressures indicated. In traces (a)–(d) the temperature was measured relative to T_c, as observed in the longitudinal response. In traces (e) and (f) the temperature was measured relative to the position of the sq mode, as observed in the longitudinal response, since the T_c signature at higher pressures was less clear than at lower pressures. The sq mode frequency was taken as $\omega=\sqrt{12/5}\Delta^+(T,P)$. The arrows indicate the position of the sq mode signature in the corresponding longitudinal sound trace.

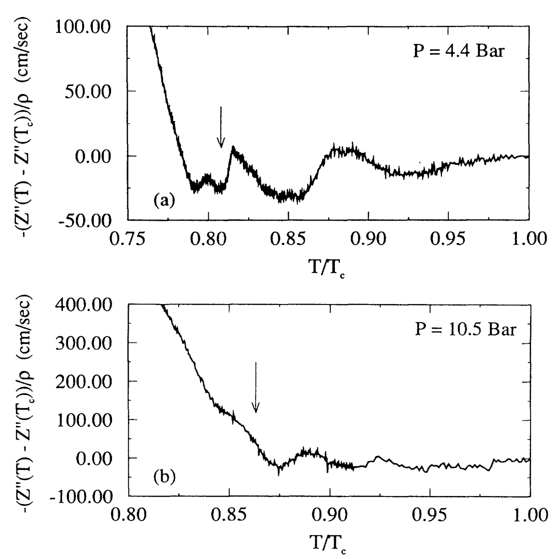

FIG. 3. Enlargement of the imaginary transverse acoustic impedance traces shown in Figs. 2(a) and 2(d), corresponding, respectively, to (a) 4.4 bars and (b) 10.5 bars. As in Fig. 2, the arrows indicate the position of the sq mode signature in the corresponding longitudinal sound trace.

locity associated with these oscillations provided the velocity was known at some reference point, which it is not. At temperatures below the sq mode it is not clear whether the contribution is from standing waves or a collective mode multiplet, or if indeed either of these make any significant contribution. The ambiguity associated with the identification of these features is due not only to the closeness of their spacing (10–50 μK), but also because the sq mode signature in the longitudinal sound did not precisely coincide with the same feature in the transverse sound for each pressure studied (for reasons discussed above).

Let us summarize the significance of our new results. First, the results of Roach and Ketterson (Ref. 8) have not only been confirmed using a different measurement technique, but have been extended to a much wider range of temperatures and pressures. Second, we have been able to firmly establish that there is a significant contribution from the $J=2^-$ (likely $J_z=\pm 1$) collective mode manifold to the behavior of the transverse acoustic impedance in superfluid ^{3}He-*B*, removing the ambiguity associated with the earlier measurements. While this does not directly provide any new information on the sq mode, it does provide an important first step towards our understanding of the nature of *transverse* sound propagation in superfluid ^{3}He-*B*. In addition, we have provided indirect verification of the recent calculations of Moores and Sauls; a direct comparison is not possible at this time, since they have made calculations of the acoustic attenuation and velocity, while our measurements are of the imaginary component of the acoustic impedance. Classically (in the hydrodynamic regime and neglecting slip effects at the liquid-transducer interface), the complex acoustic impedance is given by $Z=\rho C$, where C is the complex sound velocity. If the history of the longitudinal acoustic impedance response provides any guide, future theory will have to include the effects of not only single-particle excitations (including pair breaking), but the various collective modes as well.

This work was supported by the National Science Foundation under Grant No. DMR-89-07396. The experiments were performed in the magnet and low-temperature facility which is partially supported by the Northwestern University Materials Research Center under NSF Grant No. DMR-88-21571. We would like to acknowledge important discussions with S. Adenwalla, Bimal K. Sarma, Zuyu Zhao, J. A. Sauls, S. K. Yip, and G. F. Moores.

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