Transverse Acoustic Impedance of Normal Liquid $^3$He with $^4$He Coating

Yuta Tamura, Satoshi Murakawa, Yuichiro Wada, Masahiro Wasai, Masamichi Saitoh, Yuki Aoki, Ryuji Nomura* and Yuichi Okuda

Department of Condensed Matter Physics, Tokyo Institute of Technology, 2-12-1 Ookayama, Meguro, Tokyo 152-8551, Japan

E-mail: nomura@ap.titech.ac.jp

Abstract. We measured the transverse acoustic impedance of the normal liquid $^3$He at 16 MHz and 10 bar with and without $^4$He layers plated on a wall in the temperature range of 500 to 3 mK. The real component of the impedance gradually increased with cooling in the high-temperature hydrodynamic region and saturated in the low-temperature collisionless region. In the crossover region around 20 mK, the real component had a steep increase and the imaginary component was minimum. Overall change in the temperature dependence became smaller by $^4$He coating and we can obtain the specularity parameter $S$ of the wall by fitting the temperature dependence of the experimental impedance to the theory.

1. Introduction

How a fluid reacts to an oscillating wall is a very fundamental physical response providing information on the mechanical and hydrodynamical properties of the fluid and also on the boundary condition. Both longitudinal and transverse acoustic impedances $Z$ are defined as the ratio

$$Z = \frac{\Pi}{u},$$

where $\Pi$ is stress of the fluid on the wall and $u$ is the wall velocity[1]. Direction of the oscillation is vertical to the wall for the longitudinal and parallel for the transverse. In the hydrodynamic regime $\omega \tau << 1$ which corresponds to a high temperature in liquid $^3$He, $Z$ has a clear meaning that one can easily grasp. Here, $\omega$ is the oscillation angular frequency of the wall and $\tau$ is the collision time of the fluid particles. For the longitudinal impedance

$$Z = \rho c - \frac{i \rho c^2 \alpha}{\omega},$$

where $\rho$, $c$, $\alpha$ are the density of the fluid, velocity and damping of longitudinal sound in the fluid. Therefore, measurement of the longitudinal acoustic impedance is equivalent to measurements of the velocity and damping of sound in the fluid. For the transverse impedance

$$Z = \sqrt{\frac{\omega \eta}{2}} (1 - i),$$

where $\eta$ is the viscosity of the fluid. The fact that the real and imaginary components of $Z$ are the same value means that transverse sound does not propagate in a fluid and is critically
damped. The effect of the transverse oscillation remains only in the region within the viscous penetration depth \( \sqrt{\frac{2\eta}{\omega \rho}} \) from the wall.

However, in the collisionless region \( \omega \tau >> 1 \), at low temperatures in liquid \(^3\)He, these correspondences no longer hold and one must come back to the definition Eq. (1). Acoustic impedance measurements in normal fluid \(^3\)He have been studied extensively in the context of the first to zero sound crossover in Fermi liquid[2, 3, 4, 5, 6, 7, 8, 9, 10, 11]. Transverse acoustic impedance would detect the transverse zero sound if it propagated with large enough Fermi liquid parameters, although this has not been clearly confirmed experimentally due to an incoherent quasiparticle excitation[1]. In reality transverse sound was found to propagate only in the superfluid B phase with the help of its coupling to the imaginary squashing mode[12, 13]. Here, we report a preliminary transverse acoustic impedance measurement with and without \(^4\)He coating on a wall to learn the boundary condition for the quasiparticle scattering.

2. Experiment and Results

Our sample cell was mounted on a Cu nuclear demagnetization refrigerator precooked by a \(^3\)He-\(^4\)He dilution refrigerator. Experiments were performed in the temperature range of 500 to 3 mK. In order to measure transverse acoustic impedance an AC-cut quartz transducer of a fundamental frequency of 16 MHz was immersed in liquid \(^3\)He in the sample cell. It oscillated in the shear mode and worked as a parallel oscillating wall. Information about the momentum transfer from the oscillating wall to \(^3\)He quasiparticle can be measured as the change of load. From the \( Q \) factor and resonance frequency \( f_0 = \omega_0 / 2\pi \) of the transducer measured by the CW method described in our previous reports [14, 15, 16], each component of complex acoustic impedance \( Z = Z' + iZ'' \) was obtained as,

\[
Z' = \frac{1}{4} n\pi Z_q \Delta (1/Q),
\]

\[
Z'' = \frac{1}{2} n\pi Z_q \Delta f_0 / f_0.
\]

Here, \( Z_q \) is the acoustic impedance of quartz and \( n \) is the harmonics number of the transducer[1]. \( \Delta f_0 \) and \( \Delta (1/Q) \) represent the changes from the high temperature limit where \( Z \) should be very small.

The cell has a sintered silver heat exchanger whose surface area was 142 m\(^2\) measured by the nitrogen BET method at 77 K. The temperature was measured by a \(^3\)He melting curve thermometer (MCT) mounted on the nuclear stage and a calibrated RuO\(_2\) thermometer. To coat the surface with \(^4\)He, we introduced \(^4\)He into the cell first at 10 K and kept it overnight to achieve an equilibrium. Thereafter, \(^3\)He was introduced below 0.3 K. The thickness of \(^4\)He coverage was 2.7 layers (40.1 µmol/m\(^2\)), which was determined by the surface area of the heat exchanger and the amount of \(^4\)He gas introduced[17]. It is known from torsional oscillator measurement and fourth sound measurement that \(^4\)He layers remain inert below about 2.0 layers but alter the boundary condition above it[18, 19]. The bare surface without \(^4\)He coating is in the diffusive limit because the roughness on the atomic scale is relevant for the quasiparticle scattering. Specularity parameter \( S \) expresses the probability of the scattering conserving the parallel component of the quasiparticle momentum and \( S = 0 \) for the diffusive limit. Thick layers of \(^4\)He become superfluid and make the wall more specular, \( S > 0 \).

Figure 1a and b show the temperature dependences of \( Z' \) and \( Z'' \) at \( f_0 = 16 \) MHz and at a pressure of 10 bar. The circles and crosses are the cases of the bare surface without \(^4\)He coating and coating with 2.7 layers of \(^4\)He. \( Z' \) has a steep increase and \( Z'' \) has a minimum at around the crossover temperature \( \omega \tau \sim 1 \). Although \( Z'' \) should go to 0 in both the high and low temperature limits if the Fermi liquid theory is assumed to be applicable to the high temperature, it had
Figure 1. Temperature dependence of the real (upper panel, a) and imaginary (lower panel, b) components of the transverse acoustic impedance. The circles and crosses are the cases for the bare and coated surfaces with $^4$He. Temperature dependence becomes weaker by the coating with 2.7 atomic layers of $^4$He. Solid and dashed lines are the fitting by the Fermi liquid theory.

different values in the two limits. However, we had a large temperature dependent background of $Z''$, about 30%, which comes from the shift in $f_0$ even without liquid $^3$He and were not able to verify the limiting behavior. We have not yet succeeded in the subtraction of the rather large background and thus Fig. 1b is not the correct temperature dependence of $Z''$ but shows only the qualitative tendency.

The background change of $Z'$ was much smaller than $Z''$ and thus we could obtain a reliable temperature dependence of $Z'$. As seen in Fig. 1a, the saturated value in the low temperature limit is smaller in the coated case than in the bare case. This reduction of the temperature dependence is the result of the increase in $S$ by the coating. Intuitively specular scattering conserves the parallel component of the quasiparticle momentum and does not contribute to the transverse acoustic impedance. This is the first confirmation of the reduction of $S$ by the high frequency measurement of the transverse acoustic impedance. Smaller change by the coating is also seen in Fig. 1b.

The solid line in Fig. 1a is the fitting by the Fermi liquid theory for the bare surface or in the diffusive scattering limit. We used an analytical expression of $Z$ developed by Richardson[7]. Due to the space limitation in this report, details of the fitting cannot be described but we
followed the procedure given by Milliken et al. [8]. The expression reproduces the experiment reasonably well. However, it has been known that \(Z\) has a slight frequency dependence at low temperatures which the Fermi liquid theory cannot account for[4, 8]. In this sense \(Z\) is not yet fully understood, although it should be a very basic response of the Fermi liquid.

\[
Z(S) = (1 - S) \frac{Z(S = 0)}{1 - S + \frac{SZ(S=0)}{L}},
\]

where \(L = \frac{150}{16}, \eta\) is the viscosity and \(\lambda\) is the mean free path[9, 10]. The dashed line in Fig. 1a is the fitting by Eq. (6) and we obtain \(S = 0.2\) for 2.7 layers of \(^4\)He. Although Eq. (6) is valid only in the region \(\omega \tau < 1\) and we used it in this region, the theory reproduced the experimental result well down to much lower temperatures. The solid and dashed lines in Fig. 1b are the plot of the theoretical values using the same parameters as in Fig. 1a for comparison.

3. Summary
Temperature dependence of the transverse acoustic impedance was measured at 16 MHz and 10 bar. Measurement of the real component was reliable due to small background change and fitted well by the Fermi liquid theory. The imaginary component had larger background change and only the qualitative feature was obtained. Coating of the wall with 2.7 layers of \(^4\)He successfully altered the boundary condition and made the temperature dependence smaller than without coating. Specularity parameters are obtained as 0.2 for the coated case.

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References
[1] Halperin W P and Varoquaux E 1990 Helium Three, ed W P Halperin and L P Pitaevskii (North-Holland, Amsterdam)
[2] Keen B E, Matthews P W and Wilks J 1963 Phys. Lett. 5 5
[3] Keen B E, Matthews P W and Wilks J 1965 Proc. Roy. Soc. (London) A284 125
[4] Roach P R and Ketterson J B 1976 Phys. Rev. Lett. 36 736
[5] Flowers E G, Richardson R W and Williamson S J 1976 Phys. Rev. Lett. 37 309
[6] Flowers E G and Richardson R W 1978 Phys. Rev. B 17 1238
[7] Richardson R W 1978 Phys. Rev. B 18 6122
[8] Milliken F P, Richardson R W and Williamson S J 1981 J. Low Temp. Phys. 45 409
[9] Einzel D, Wölffe P and Hirschfeld P J 1990 J. Low Temp. Phys. 80 31
[10] Einzel D and Parpia J M 1997 J. Low Temp. Phys. 109 1
[11] Aoki Y, Wada Y, Sekimoto Y, Yamaguchi W, Ogino A, Saitoh M, Nomura R and Okuda Y 2004 J. Low Temp. Phys. 134 945
[12] Lee Y, Haard T M, Halperin W P and Sauls J A 1999 Nature 400 431
[13] Kalbfeld S, Kucera M M and Ketterson J B 1993 Phys. Rev. Lett. 71 2264
[14] Aoki Y, Wada Y, Saitoh M, Nomura R and Okuda Y 2005 Phys. Rev. Lett. 95 075301
[15] Aoki Y, Wada Y, Ogino A, Saitoh M, Nomura R and Okuda Y 2005 J. Low Temp. Phys. 138 783
[16] Saitoh M, Wada Y, Aoki Y, Murakawa S, Nomura R and Okuda Y 2006 Phys. Rev. B. 74 220505
[17] Freeman M R and Richardson R C 1990 Phys. Rev. B 41 11311
[18] Kim D, Nakagawa M, Ishikawa O, Hata T, Kodama T and Kojima H 1993 Phys. Rev. Lett. 71 1581
[19] Tholen S M and Parpia J M 1992 Phys. Rev. Lett. 68 2810