High-Frequency Acoustics of ^{3}He in Aerogel

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High-frequency (~15 MHz) acoustics were performed on ^{3}He in 98% porous silica aerogel using an acoustic cavity technique. Measurements of the sound attenuation in the normal Fermi liquid and superfluid display behavior quite different from the bulk owing to strong elastic scattering of quasiparticles. The transition from first-to-zero sound is completely obscured with a quasiparticle mean-free path estimated to be in the range of 200–300 nm. No collective mode attenuation peak was observed at or below the superfluid transition.

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The purest material in nature is liquid ^{3}He at mK temperatures. Its transition to a p-wave superfluid state at $T_{c0} \sim 2.5$ mK was discovered in 1972 [1]. Since then, extensive studies have provided a firm understanding of its unconventionally paired state, but only in the clean limit. Recently there has been considerable interest in unconventional pairing in high-temperature superconductors and certain heavy fermion materials where magnetic and nonmagnetic impurity scattering can suppress superconductivity. This provides some of the motivation for the study of ^{3}He superfluidity in highly porous aerogel, since the aerogel has the relevant length scales for probing dilute impurities in superfluid ^{3}He. The p-wave Cooper pairs of ^{3}He are scattered by silica strands of only 3 nm in diameter, much less than the bulk coherence length, ξ_0, which varies with pressure from 16 nm (melting pressure) to 77 nm (zero pressure). The pair-breaking process is described by one parameter given by the model for homogeneous and isotropic scattering as the ratio ξ_0/l, where l is in the mean free path of ^{3}He quasiparticles. This pair breaking can be "tuned" by pressure although, until now, there has been only limited direct experimental information on the mean-free path itself.

Superfluidity of ^{3}He in aerogel was discovered by torsional oscillator measurement [2] which probes the superfluid density and nuclear magnetic resonance (NMR) [3,4] from which information on spin susceptibility and pairing amplitude has been obtained. These experimental findings have provoked theoretical work aimed at understanding the suppression of superfluidity in the presence of impurity scattering [5–8] and the transport properties of the "dirty" Fermi liquid [9,10]. However, even the experimental identification of the superfluid phase diagram in aerogel deduced from these measurements [3,4], and subsequent NMR experiments [11,12], remains unclear. Low-frequency sound (~Hz–kHz) measurements have been performed by Golov and co-workers [13], giving a better picture of the superfluid density; however, high-frequency sound (~1–100 MHz) which has proven to be a powerful probe to study the first-to-zero sound transition in the ^{3}He Fermi liquid, and which couples strongly to the order parameter collective modes of the superfluid, has yet to be explored. In this Letter, we report on results from high-frequency acoustics ($f \sim 15$ MHz) in which the attenuation of longitudinal sound in ^{3}He normal and superfluid near 16 bar pressure was measured in a 98% porous aerogel sample using an acoustic cavity technique.

The acoustic cavity was formed with two quartz transducers separated by two wire spacers [14]. One transducer was AC cut for transverse sound and the other was X cut for longitudinal sound, both of quartz and with a diameter of 9.5 mm. Their fundamental frequencies were 4.8 and 2.9 MHz, respectively. This arrangement permitted experiments with either transverse or longitudinal sound waves. During the aerogel preparation, the transducers were held by a stainless steel jig, and the cavity separation d was defined by two stainless steel parallel wires of diameter $d = 254\ \mu$m, as shown in the lower inset of Fig. 1. The aerogel was grown *in situ* in the volume between the transducers. Each quartz transducer has two active sides: one probes the aerogel-filled cavity and the other the bulk ^{3}He liquid outside the cavity.

The electrical impedance of the transducer was measured by using a continuous wave frequency-modulated spectrometer [15]. The measurements were performed at a fixed frequency at odd harmonics of the transducers, with a frequency modulation of 400 Hz and modulation amplitude of 3 kHz. Small changes in the acoustic impedance, $Z = \rho\omega/q$, produced changes in the electrical impedance of the transducers, where ρ is the density of the medium, ω is the sound angular frequency, $q = k + i\alpha$ is the complex wave number, and $k = 2\pi/\lambda$, where λ is the wavelength and α is the attenuation. In a low-attenuation medium, a sound wave is reflected from the cavity wall boundary, and an interference occurs between the source and reflected waves. Varying the phase velocity $c = \omega/k$ with pressure or temperature produces oscillations in the detected impedance with a period corresponding to $\Delta\lambda \simeq \lambda^2/2d$, as is evident in the data in Fig. 1.

In the upper inset of Fig. 1, we show the longitudinal acoustic response measured as the pressure was slowly decreased from $P \sim 20$–4 bars, at a temperature of 60 mK

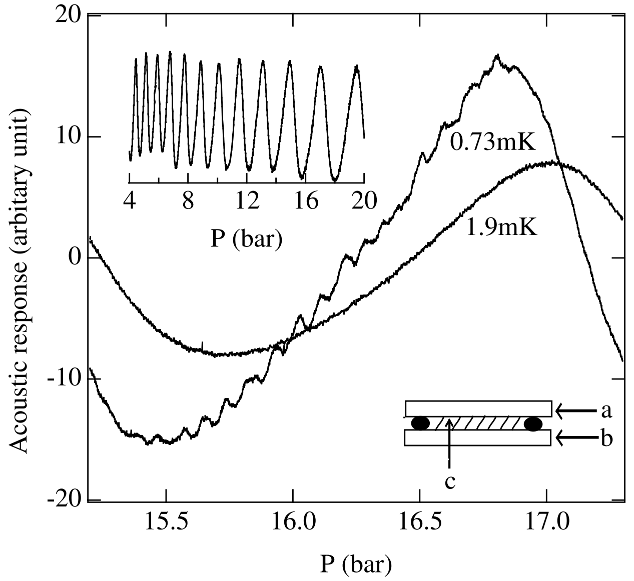

FIG. 1. Acoustic response for longitudinal sound at 14.635 MHz during a slow depressurization ($\sim$24 h) in the pressure range $P \sim 15-17.5$ bars for $T = 0.73$ and 1.9 mK. Upper inset: the acoustic response for a larger pressure range is shown at $T = 60$ mK. Lower inset: the acoustic cavity (c), between longitudinal (a) and transverse (b) transducers, is filled with silica aerogel of 98% porosity.

and a fixed frequency of 14.635 MHz. The regular oscillatory pattern demonstrates existence of a well-defined sound mode in the cavity. An expanded view is shown in the main part of the figure for $T = 0.73$ and 1.9 mK. At 0.73 mK the larger signal amplitude indicates that there is a lower attenuation in the superfluid-aerogel medium, as compared to the normal fluid. The smaller amplitude, higher-frequency, modulation that is superimposed on the data, originates from bulk ^{3}He superfluid outside the cavity and can be easily taken into account in the analysis (Fig. 2). We have also measured the transverse acoustic response near T_{c0} as shown in the inset of Fig. 3, at 8.692 MHz and a pressure of 15.6 bars. There is a well-defined acoustic signature of the bulk superfluid transition that provides a calibration for the lanthanum-doped cerium magnesium nitrate thermometer.

The temperature dependence of the attenuation $\alpha(T)$ can be determined from the acoustic response $A(T)$ (Fig. 1). In a cavity, multiple reflections occur between the transducer-^{3}He interfaces, and it can be shown that the attenuation satisfies the equation,

$$e^{-4\alpha d} + \frac{A_0}{A(T)}\left(\frac{1}{R^4} - 1\right)e^{-2\alpha d} - \frac{1}{R^4} = 0, \quad (1)$$

where $A_0 \equiv \lim_{\alpha\to 0} A(T)$ is the zero-attenuation limit of the oscillation amplitude, and R is the coefficient of reflection accounting for all losses other than the attenuation of the medium itself. Equation (1) can easily be solved for the attenuation α. The zero-attenuation amplitude A_0 is taken from the largest amplitude observed ($P \sim 25$ bars) at the lowest temperature ($T \sim 0.6$ mK). The coefficient

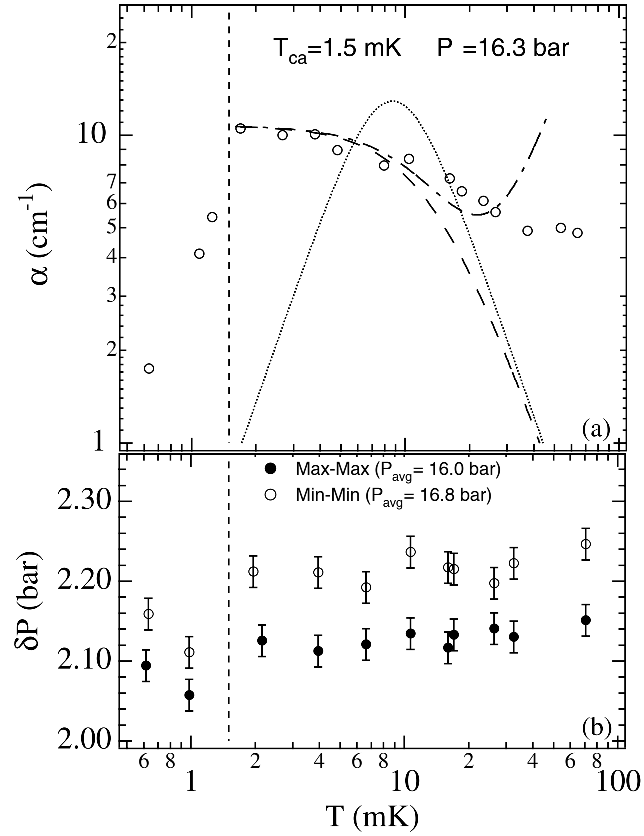

FIG. 2. (a) Temperature dependence of the attenuation of longitudinal sound at 14.635 MHz for ^{3}He in aerogel for depressurization in the range $P \sim 15.5-17.0$ bars. The long-dashed line is the attenuation calculated by the viscoelastic model and the dot-dashed line includes the decoupling effect (see text). For comparison the attenuation in bulk ^{3}He (dotted line) is shown. The vertical dotted line is the aerogel superfluid transition temperature. (b) The pressure interval δP for one acoustic oscillation as a function of temperature. P_{avg} is the average pressure.

of reflection R cannot be determined independently. We can choose R such that the pressure dependence of the attenuation observed at low temperatures just above T_{ca} reproduces the pressure dependence calculated by the viscoelastic model, including the aerogel mean free path, which we discuss below. The pressure dependence of the attenuation and details of the present analysis will be published elsewhere [16].

In Fig. 2a the attenuation of longitudinal sound $\alpha(T)$ is shown for ^{3}He normal and superfluid in 98% aerogel. We also show with a dotted line the attenuation in the bulk Fermi liquid for the same experimental conditions. The difference between the bulk and dirty Fermi liquid is striking as the attenuation of sound in aerogel saturates below a temperature $T \sim 6$ mK that completely obscures the crossover from hydrodynamic (first) to collisionless (zero) sound that occurs near 10 mK for pure ^{3}He. Note that the attenuation remains in this impurity-dominated regime for temperatures between the bulk and aerogel superfluid transitions, $T_{ca} < T < T_{c0} = 2.1$ mK, but drops rapidly for temperatures below the aerogel

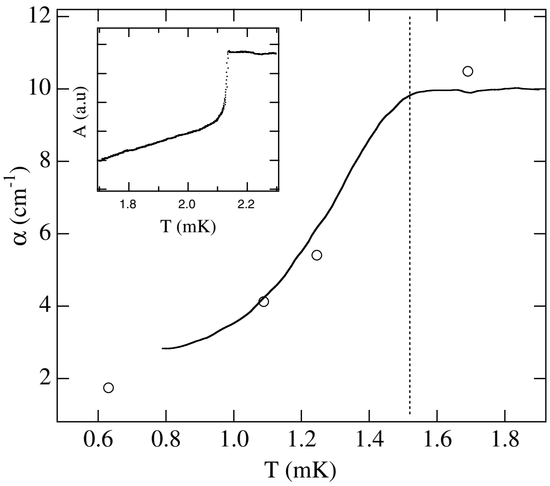

FIG. 3. Temperature dependence of the attenuation of longitudinal sound below the superfluid aerogel transition measured with the continuous method (solid line) for the pressure range $P \sim 15.5-17.0$ bars. The open circles are the attenuation obtained with the discrete method (Fig. 2). The inset is an example of transverse acoustic response at 8.692 MHz, showing the bulk superfluid transition.

transition $T_{ca} = 1.5$ mK at $P = 16.3$ bars. The vertical dotted line shown in this graph indicates the aerogel superfluid transition determined from the longitudinal acoustic response as the temperature was slowly varied and the pressure kept constant. The aerogel superfluid transition temperatures T_{ca}, observed in our sample, are in very good agreement with previously reported values for similar density aerogels [4,17,18].

The temperature dependence of the oscillation period $\delta P(T)$ between two maxima, or two minima, in the pressure region $\sim$15–18 bars are plotted in Fig. 2b. We can relate the oscillation period δP to the sound velocity, expanding c to first order in δP,

$$\delta P(T) = \frac{c^2(T)}{[2df - c(T)]\frac{\partial c}{\partial p}(T)}. \tag{2}$$

The phase velocity c can be inferred from measurements of the pressure dependence of δP [16]. We consistently observe temperature independence of δP in the normal fluid and a small ($\sim$2%) drop on cooling into the superfluid state of approximately the magnitude expected for the velocity changes ($\sim$1%) observed at the transition in bulk superfluid ^{3}He. In the bulk normal fluid, at the transition from first-to-zero sound, there is a velocity change of the same magnitude. But this is not evident in our aerogel ^{3}He data, although it might be below the resolution of the experiment, $\sim$1%.

A viscoelastic model [19,20] provides a phenomenological description of the crossover region from first-to-zero sound in normal ^{3}He by introducing a single relaxation time τ and is consistent with the relaxation time approximation in Fermi liquid theory. In this model, the attenuation is expressed as

$$\alpha_1(T) = \frac{c_0 - c_1}{c_1^2}\frac{\omega^2\tau}{1 + (\omega\tau)^2}, \tag{3}$$

where c_1 and c_0 are the velocity of first and zero sound, respectively. We write the total relaxation time τ as

$$\frac{1}{\tau} = \frac{1}{\tau_\eta} + \frac{1}{\tau_a}, \tag{4}$$

where τ_η is the viscous relaxation time for bulk ^{3}He and τ_a is the collision time between the quasiparticles and the aerogel. With this model, we find that $R \sim 0.8$ and the aerogel mean-free path is in the range 200–300 nm. The long-dashed line in Fig. 2a shows the attenuation as calculated by the viscoelastic model with an aerogel mean-free path of 240 nm. The mean-free path estimated from the data is slightly higher than that of previous theoretical and numerical estimates for a 98% aerogel (175 nm, Rainer and Sauls [21], 130 nm, Porto and Parpia [18], and 200 nm, Haard *et al.* [22]).

It is evident from the data that another process occurs above 10 mK which prevents the attenuation from recovering the viscoelastic attenuation at higher temperature. It is known that sound propagating in a porous medium filled with a viscous liquid is highly attenuated when the viscous penetration depth is of the order of the pore size [23]. The viscous penetration depth of ^{3}He, $\delta = \sqrt{2\eta/\rho\omega} \propto 1/T$, is approximately 500 nm at 10 mK and 100 nm at 50 mK, which is on the right length scale for the liquid to decouple from the aerogel. For a porous medium with a well-defined pore size, the decoupling of the fluid is inversely proportional to the viscosity in the highly viscous limit and so the attenuation should be proportional to T^2 [24]. The dot-dashed line in Fig. 2a shows the result of the calculated attenuation when a contribution of the form $\alpha_2 = pT^2$ is added to Eq. (3), with $p = 0.005$ cm^{-1} mK^{-2}. However, the data cannot be reproduced with any value of the parameter p, suggesting that the highly distributed structure of the aerogel should be explicitly taken into account in a theory describing correctly the decoupling of the ^{3}He liquid from the aerogel.

In Fig. 2a, the attenuation of sound was obtained from a set of discrete temperature measurements at which $A(T)$ was measured during a slow depressurization. This method is not suitable for extracting the attenuation near the aerogel superfluid transition T_{ca}. It is nevertheless possible to measure the attenuation continuously as a function of the temperature in the superfluid. To achieve this, the temperature was slowly varied while the pressure was kept constant and chosen to correspond to the maximum (16.9 bars) and then, in a separate experiment, to the minimum (15.6 bars) of the acoustic response, as in Fig. 1. The difference between the two measurements, interpreted as a change in attenuation, is plotted in Fig. 3. One striking feature of the continuous data is that, unlike the bulk superfluid [19,25], there is no attenuation peak just below T_{ca} as might be expected from an order parameter collective mode (OPCM) and pair breaking. We estimate our sensitivity in the continuous temperature method to be at least $\sim$0.1 cm^{-1}.

It is reasonable to assume that the transducer wall produces a uniform order parameter texture based on inferences made from previous NMR experiments on superfluid in aerogel [3,12]. In the case of an A phase, the angular momentum $\hat{l}$ vector would be aligned perpendicular to the wall, and the sound wave in this geometry *does not couple to any OPCM*. At low frequencies, $\sim$15 MHz, the OPCM is the dominant contribution to the attenuation peak observed in the bulk superfluid. The remaining pair-breaking contribution to the attenuation is weak and is spread over a wide range of temperatures. For a B phase, one would expect the $\hat{n}$ vector to be normal to the wall. For this configuration, the bulk superfluid gives rise to a significant contribution to the attenuation just below T_c from the imaginary squashing mode [19]. We do not observe any extra attenuation below T_{ca}. If the superfluid is a B phase this collective mode must be severely broadened or suppressed in aerogel.

In conclusion, high-frequency acoustics were performed in normal and superfluid ^{3}He in the presence of strong quasiparticle scattering from a 98% porous silica aerogel. The attenuation from quasiparticle elastic scattering in the Fermi liquid completely obscures the transition from first-to-zero sound. Of particular interest is the absence of any collective mode attenuation peak below the aerogel superfluid transition.

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[1] D. D. Osheroff *et al.,* Phys. Rev. Lett. **28**, 885 (1972).
[2] J. V. Porto and J. M. Parpia, Phys. Rev. Lett. **74**, 4667 (1995).
[3] D. T. Sprague *et al.,* Phys. Rev. Lett. **75**, 661 (1995).
[4] D. T. Sprague *et al.,* Phys. Rev. Lett. **77**, 4568 (1996).
[5] G. E. Volovik, Pis'ma Zh. Eksp. Teor. Fiz. **63**, 281 (1996) [JETP Lett. **63**, 301 (1996)].
[6] E. V. Thuneberg *et al.,* Phys. Rev. Lett. **80**, 2861 (1998).
[7] G. Baramidze and G. Kharadze, Zh. Eksp. Teor. Fiz. **115**, 754 (1999) [Sov. Phys. JETP **88**, 415 (1999)].
[8] S. Higashitani, J. Low Temp. Phys. **114**, 161 (1999).
[9] D. Einzel and J. M. Parpia, Phys. Rev. Lett. **81**, 3896 (1998).
[10] P. Vankataramani and J. A. Sauls, Physica (Amsterdam) **284B**, 589 (2000).
[11] B. I. Barker *et al.,* J. Low Temp. Phys. **113**, 635 (1998).
[12] H. Alles *et al.,* Phys. Rev. Lett. **83**, 1367 (1999).
[13] A. Golov *et al.,* Phys. Rev. Lett. **82**, 3492 (1999).
[14] Y. Lee *et al.,* Nature (London) **400**, 431 (1999).
[15] Y. Lee *et al.,* J. Low Temp. Phys. **103**, 635 (1996).
[16] G. Gervais *et al.* (to be published).
[17] K. Matsumoto *et al.,* Phys. Rev. Lett. **79**, 253 (1997).
[18] J. V. Porto and J. M. Parpia, Phys. Rev. B **59**, 14 583 (1999).
[19] W. P. Halperin and E. Varoquaux, in *Helium Three,* edited by W. P. Halperin and L. P. Pitaevski (Elsevier, Amsterdam, 1990), p. 255.
[20] I. Rudnick, J. Low Temp. Phys. **40**, 287 (1980).
[21] D. Rainer and J. A. Sauls, J. Low Temp. Phys. **110**, 525 (1998).
[22] T. M. Haard *et al.,* Physica (Amsterdam) **284B-288B**, 289 (2000).
[23] K. Warner and J. R. Beamish, Phys. Rev. B **50**, 15 896 (1994).
[24] M. A. Biot, J. Acoust. Soc. Am. **28**, 168 (1956); **28**, 179 (1956).
[25] J. C. Wheatley, Rev. Mod. Phys. **47**, 415 (1975).