

# Acoustic Properties of Normal Liquid $^3\text{He}$ in 98% Aerogel

H.C. Choi · N. Masuhara · B.H. Moon ·  
P. Bhupathi · N. Mulders · M.W. Meisel · Y. Lee

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**Abstract** We have performed longitudinal ultrasound (9.5 MHz) attenuation and sound velocity measurements in the normal state of liquid  $^3\text{He}$  in 98% aerogel. The absolute attenuation and sound velocity were determined by direct propagation of sound pulses through the medium in a wide range of temperatures,  $2\text{ mK} < T < 200\text{ mK}$ . Due to the scattering off the aerogel, the sound excitation remains as first sound over the entire range of temperatures and pressures studied. Unlike pure liquid  $^3\text{He}$ , the sound attenuation shows a minimum around 30–50 mK, depending on the pressure. We report our results of absolute sound attenuation measurements at 29 bars of sample pressure.

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## 1 Introduction

One of the most fascinating vestiges of a Fermi liquid is the existence of zero sound. Zero sound emerges as a well defined mode at low temperatures where the conventional hydrodynamic condition breaks down, as beautifully demonstrated in liquid  $^3\text{He}$  by Abel, Anderson and Wheatley [1]. As temperature decreases, the quasi-particle scattering time,  $\tau$  ( $\propto 1/T^2$ ) becomes longer, and the crossover from the hydrodynamic region ( $\omega\tau \ll 1$ ) to the collisionless region ( $\omega\tau \gg 1$ ) occurs at a fixed sound frequency. However, in the presence of impurity scattering, as is the case in

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H.C. Choi (✉) · N. Masuhara · B.H. Moon · P. Bhupathi · M.W. Meisel · Y. Lee  
Microkelvin Laboratory, Department of Physics, University of Florida, Gainesville,  
FL 32611-8440, USA  
e-mail: hyuncc@phys.ufl.edu

N. Mulders  
Department of Physics and Astronomy, University of Delaware, Newark, DE 19716, USA

high porosity aerogel, the quasi-particle scattering is ultimately limited by the temperature independent impurity scattering at low temperatures. The effect of impurity scattering on liquid  $^3\text{He}$  impregnated in high porosity aerogel has been an active subject for a decade [2].

In 2000, Nomura et al. conducted high frequency sound (14.6 MHz) attenuation measurements of liquid  $^3\text{He}$  in 98% aerogel at 16 bars using an acoustic cavity technique [3]. They found that the crossover from first to zero sound was effectively obscured by the impurity scattering off aerogel strands below  $\approx 10$  mK. This behavior was rather easily understood in the framework of a simple viscoelastic model. However, this approach failed to explain their results at higher temperatures, where the inelastic scattering between the quasi-particles is dominant. Furthermore, the sound attenuation in aerogel was found to saturate around 50 mK rather than follow a  $1/T^2$  dependence as in bulk. Higashitani et al. attempted to explain their results by incorporating a collision drag effect [4, 5].

The acoustic cavity technique using a continuous wave excitation is not suitable in determining absolute attenuation and sound velocity. We have successfully measured the absolute sound attenuation and velocity by propagating short sound pulses through the medium. The speed of sound was determined from the time of flight and the absolute attenuation was extracted from the multiple echoes observed in the low attenuation regime.

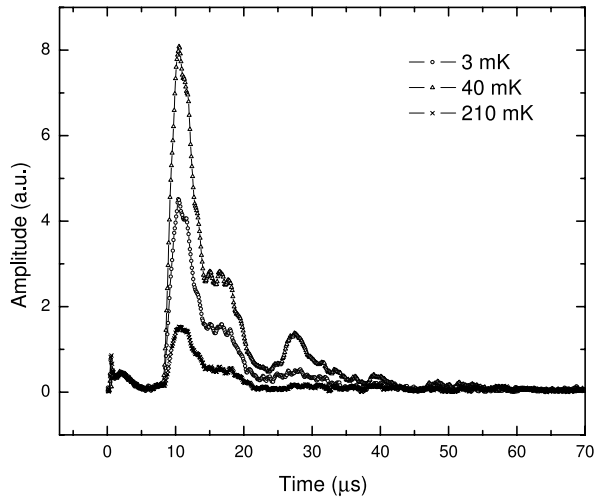
## 2 Experiments

The design of the experimental cell is similar to the one used in our previous experiment [6], and it consists of a pure silver base with  $9\text{ m}^2$  of silver sinter and a coin silver enclosure. The ceiling of the enclosure forms a diaphragm, so the cell pressure can be monitored capacitively. Two matched 9.5 MHz  $\text{LiNbO}_3$  longitudinal sound transducers are separated by a macor holder maintaining a 3 mm gap between them. To ensure the contact between the transducer surface and the aerogel, the aerogel sample was grown between the transducers. Using a commercial LIBRA/NMRkitII spectrometer, a  $1\ \mu\text{s}$  pulse was excited by a transducer (transmitter) and the response of the other transducer (receiver) was monitored. A  $^3\text{He}$  melting pressure thermometer (MPT) was adopted as the main thermometer above the solid ordering transition, and temperatures below 1 mK were determined by a Pt NMR thermometer located right next to the sample cell and the MPT. A 1 MHz AC cut quartz transducer was embedded in bulk liquid to monitor bulk acoustic response and was used to crosscheck thermometer calibration. Additional experimental details are described elsewhere in this issue [7].

## 3 Results

The receiver signals from the spectrometer at three different temperatures are shown in Fig. 1. Each signal is the result of averaging 8 phase alternating pulses. The zero on the time axis indicates the end of the  $1\ \mu\text{s}$  excitation pulse. The location of the rising edge of the signal depends on the sample pressure, and the signal disappears when

**Fig. 1** Receiver signal outputs from the spectrometer at three different temperatures at 29 bars. Detection is triggered at the falling edge of the excitation pulse of 1  $\mu$ s



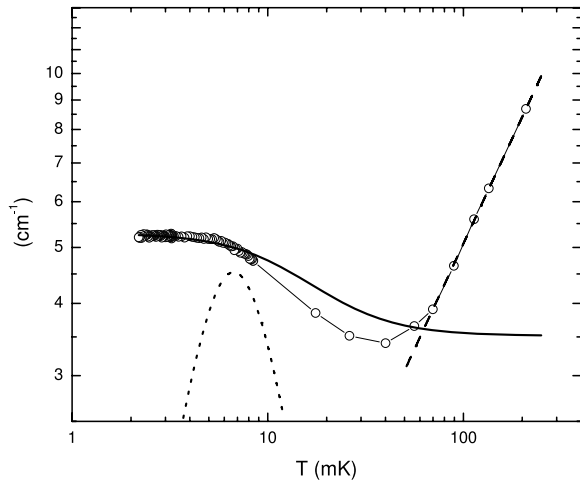
the sample cell is completely evacuated. These observations assure that the detected signal at the receiver side is from the sound pulse passing through the aerogel/liquid. Broadening of the excitation pulse is mainly caused by the ringing of the transducers. The step-like shape is due to a slight mismatch of the two transducer spectra. The normalized receiver signals, taken at different temperatures, collapse into the same shape, indicating that the transducer spectra remain unchanged throughout the measurement.

A strong temperature dependence of the detected signal amplitude is clearly demonstrated in Fig. 1. Two different methods are used to calculate the relative attenuation. One is to use the peak value of the receiver signal and the other is to use the area under the signal by integration. Both methods produce consistent results within 1% in the low attenuation regime and within, at most, 5% in the highest attenuation regime. Here, we present our attenuation data obtained by the second method. The relative attenuation is converted into the absolute attenuation from a reference point at 0.4 mK and 29 bars where 3 echoes can be clearly observed [7].

Figure 2 shows the absolute sound attenuation as a function of temperature along with the sound attenuation in bulk (dotted line). Unlike the bulk, the zero to first sound crossover feature is absent.<sup>1</sup> Higashitani et al. calculated a dispersion relation considering the momentum transfer from a quasi-particle to the elastic aerogel strand. They argue that this collision process generates a drag force and accordingly the motion of the aerogel itself. Therefore, an additional contribution, originating from friction between aerogel and the liquid motion, needs to be added. In this case, the aerogel moves together with the liquid, and the sound speed needs to be modified by  $c_f^2 = c_1^2 / (1 + \rho_a / \rho)$ , where  $c_f$  is the sound velocity in aerogel/liquid,  $c_1$  is the first sound velocity in bulk, and  $\rho(\rho_a)$  represents density of liquid (aerogel). From our measurements, the sound velocity of 330 m/s is calculated by the time

<sup>1</sup>The receiver signal at higher harmonics could not be detected at all temperatures. This also supports the fact that the excitation remains as first sound.

**Fig. 2** Absolute attenuation above the aerogel superfluid transition at 29 bars (circle). The thicker solid line is the result of a fit based on the theory of Higashitani et al. (see text). The dotted line indicates attenuation in bulk at the same pressure. The high temperature part is fit to  $T^{0.7}$  (dashed line)

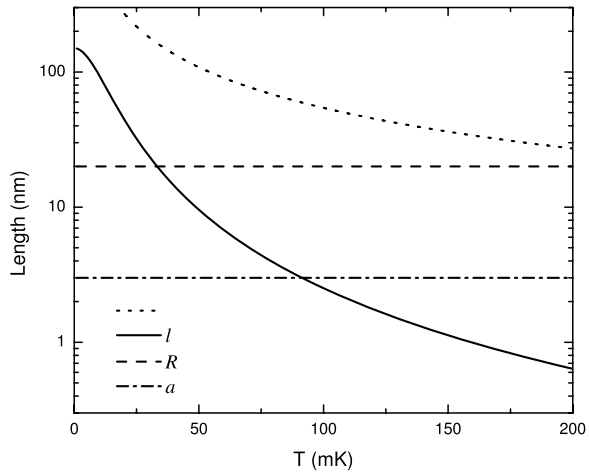


of flight method from the location of the rising edge of the receiver signal. This value is 20% lower than that of bulk at the same pressure. With  $\rho_a = 0.044 \text{ g/cm}^3$ ,  $\rho = 0.114 \text{ g/cm}^3$ , and  $c_1 = 398 \text{ m/s}$ , we get  $c_f = 338 \text{ m/s}$ , which is in excellent agreement with our measured value. For the whole temperature range, the sound velocity remains constant within 1%.

The low temperature part of the attenuation is quite similar to those of Nomura et al. [3]. However, our results show quite different behavior above 40 mK. A broad minimum appears around  $T_M = 40 \text{ mK}$  and the attenuation continues to increase with temperature for  $T > T_M$ . Interestingly, Normura et al. expected a similar rise in attenuation at high temperatures by considering the decoupling of liquid from aerogel, although their experimental results did not follow their prediction. In general, decoupling of liquid from the hosting porous medium occurs when the viscous penetration depth,  $\delta = \sqrt{2\eta/\rho\omega}$  ( $\eta \equiv$  viscosity) is of the order of the average pore size. This sloshing motion of the porous medium and viscous liquid provides an extra damping mechanism. Since the viscous penetration depth of  $^3\text{He}$  is proportional to  $1/T$ , they argued that the condition for decoupling would be satisfied at a certain temperature. Furthermore, by invoking Biot's theory [8], they projected a  $T^2$  dependence of attenuation in the high temperature region. However, our high temperature data can be best fit to  $T^{0.7}$  for all sample pressures that we studied [9].

Aerogel possesses a unique porous structure. There is no well-defined pore size and furthermore, the nano-scale strand diameter is much smaller than any other length scale involved in the  $^3\text{He}$ /aerogel system up to  $\approx 70 \text{ mK}$ . In Fig. 3, we show several relevant length scales estimated for 98% porosity aerogel: the effective mean free path,  $\ell$ , including aerogel scattering, the viscous penetration depth of  $^3\text{He}$ ,  $\delta$ , the average distance between aerogel strands,  $R = 20 \text{ nm}$ , and the radius of aerogel strand,  $a = 3 \text{ nm}$  [10]. At all temperatures shown,  $\delta$  is larger than any other length scales. However, it is interesting to notice that the attenuation minimum ( $T_M$ ) occurs around the temperature where  $\ell$  crosses  $R$ . For  $T < T_M$ ,  $\ell > R$  and the hydrodynamic description for the motion between aerogel and liquid ceases to be valid. Currently, we do not have an explanation for the origin of the  $T^{0.7}$  dependence at  $T > T_M$ .

**Fig. 3** Comparison of the relevant length scales for  $^3\text{He}$  in 98% aerogel.  $\ell$ : effective mean free path,  $\delta$ : viscous penetration depth,  $R$ : average distance between aerogel strands,  $a$ : average diameter of aerogel strand (see text)



## 4 Summary

The absolute sound attenuation and sound velocity have been measured in the normal phase of liquid  $^3\text{He}$  in 98% aerogel at 29 bars up to 200 mK. The attenuation shows a minimum at  $T_M \approx 40$  mK and follows a power law,  $T^{0.7}$ , for  $T > T_M$ . The sound velocity is reduced from the bulk value at the same pressure by 20% and remains constant for the whole temperature range.

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