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Frequency dependence of fast mode ultrasound attenuation of liquid ^{4}He in aerogel

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Abstract. In our previous work, anomalous sound attenuation in superfluid phase was observed in liquid ^{4}He filled in 97.0 % porous aerogel using longitudinal ultrasound at the frequency of 10 MHz. To understand the nature of the observed anomaly one needs to know the viscous coupling between normal component and aerogel strands. As far as the viscous penetration depth depends on frequency in the present work we have measured longitudinal ultrasound propagation in liquid ^{4}He filled in 97.0 % porous aerogel at the frequencies 6, 10, and 15 MHz. In the normal phase the sound velocity had no frequency dependence and was reduced from that of bulk liquid, since the sound velocity in aerogel is smaller than in bulk liquid helium. The attenuation in normal phase is discussed using a viscoelastic theory. The obtained results indicated that the ultrasound experiment in normal phase was performed in low frequency or crossover regime.

1. Introduction

Acoustic properties of porous fluid-filled media attract attention from both physical and technological point of view. There are several advantages in using liquid helium to probe porous media[1]. Superfluid helium in aerogel is of interest because it has a normal component that plays the role of viscous fluid and simultaneously a superfluid component with zero viscosity. It was recognized that for liquid helium in high-porous media like aerogel the normal fluid, though locked to the substrate, drags the substrate along and one needs to consider the normal-fluid motion with taking into account a restoring force as well as addition of substrate mass[2, 3]. It was observed that two sound modes, a slow critical mode, and a fast one, which resembles first sound could propagate.

Silica aerogels are made by a sol-gel process and hypercritical dried in order to obtain a high porosity glass. The structure is described as a network of silica strands with a fractal structure in the range of typical lengths between 10 and 100 Å [4]. It is of great interest to understand the way that heterogeneity the characteristic length smaller than the acoustic wavelength affects the nature of the wave propagation.

We have reported acoustic properties of liquid helium in aerogel using longitudinal ultrasound and the different behavior from rigid porous material[5, 6]. In the previous work, an anomalous attenuation maximum was observed in superfluid phase with 97% open aerogel at the frequency of 10 MHz[7].

In order to elucidate the acoustic properties in porous materials, the obvious way is to make measurements by varying the sound frequency and using materials that have different pore structure. We therefore measured sound velocity and attenuation at various frequencies using the same aerogel because coupling between aerogel matrix and helium could be changed by varying the viscous penetration depth.

2. Experiment

The ultrasonic measurements were made using a standard pulse transmission and a phase sensitive detection technique described early[5, 6]. The aerogel with 97.0% porosity has been made by Matsushita Electric Works, Ltd. The sample was machined into a cylinder of 7 mm in diameter and 2.3 mm in length. We could not observe harmonics due to large attenuation. Thus, three pairs of transducers with fundamental frequencies of 6, 10, and 15 MHz were used. In order to change transducers the sample was warmed to room temperature. The sound cell in which the aerogel was sandwiched between two $LiNbO_3$ transducers with springs enabled to do all the measurements with a single sample. Liquid ^{4}He was filled in the normal phase since it has small surface tension. We have confirmed no change in velocity and attenuation after warming up to room temperature and cooling down again in the run at 10 MHz. No damage in aerogel was observed when we changed transducers.

The resolution of sound velocity was about 10^{-5}. Absolute velocity was obtained by the flight-time of the signal, so that the absolute value was determined within about 2%. Relative attenuation change was observed with a resolution of about 0.01 dB. In order to determine absolute attenuation, the losses from signal line and transmission through transducers were evaluated from the different experiment in which bulk liquid was measured using the same sets of transducers.

3. Results and discussion

The pore size D, and the viscous penetration depth δ play important role in the ultrasound propagation in helium-filled porous media. Viscous penetration depth within which fluid viscously couples to the solid wall is given as $(2\eta/\rho_f\omega)^{1/2}$ using viscosity η, fluid density ρ_f, and angular frequency of sound ω. In the low frequency limit for $\delta \gg D$, all helium is viscously locked into the motion of the pore wall. Conversely, in the high frequency regime for $\delta < D$, only fluid within the viscous penetration depth is locked to the pore wall. When the fluid can be decoupled from the solid substrate by frequency increase, the corresponding change in the velocity and attenuation is expected.

Now we consider the length scale in our system. A dip in sound velocity and a sharp peak in attenuation corresponding to superfluid transition were observed at lower temperature than ones in bulk liquid. Taking into account the relation between T_c reduction and pore diameter[8] we get for our 97.0% open aerogel the pore diameter about 32 nm. Measurements of solidification pressure elevation in the same aerogel also gave similar critical pore size[9]. Numerical simulation of the structure of aerogel gives widely distributed but similar silica distance[4]. The viscous penetration depth of liquid helium in normal phase which depends on both frequency and pressure changes from about 25 to 50 nm. So we can propose that the present measurements have been done in the low frequency or crossover regime where in the normal fluid is coupled to aerogel strands incompletely.

Further we mainly focus on the results in normal phase. Figure 1 shows the ultrasound velocity at 2.5 K at the three frequencies as a function of pressure. For comparison, those of bulk helium obtained in a different run were plotted as well. One can see that velocity increasing with pressure in our system is governed by the velocity increase of the liquid helium but the smaller slope of this dependence reflects the influence of aerogel. The similar behavior was

observed for dense aerogels [6] but here the value of ultrasound velocity is lower than in dense aerogels [6] because of the higher porosity and smaller elastic constant of the 97% aerogel.

Frequency independent sound velocity in our experiments indicates that we still remained in the same frequency regime.

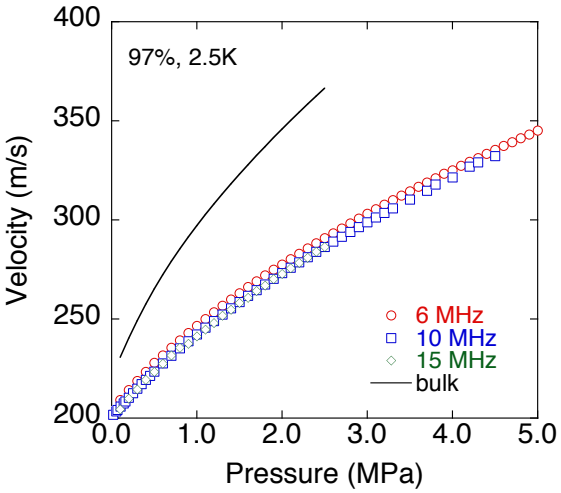


Figure 1. Sound velocity for 97 % aerogel at 2.5 K as a function of pressure. Those at 6, 10, and 15 MHz are shown and that in bulk is also shown for comparison.

Temperature variation of the attenuation was small in the normal phase at the frequencies used. Thus, we plot attenuation at 2.5 K as a function of frequency in Fig. 2. Attenuation looks to have the frequency dependence close to linear and can be approximated by a power law dependence with exponent about 1.1. The observed attenuation cannot be ascribed only to liquid helium because aerogel with high porosity would have a large attenuation. For other porous materials, liquid contribution of attenuation is obtained by subtracting attenuation without helium[10]. It is not obvious that this evaluation is useful for the composite system like highly porous aerogel and liquid.

Accordingly to the viscoelastic theory the large attenuation in the low frequency regime is caused by the motion of the fluid inside whole pores, while in the high frequency regime, attenuation would occur in a thin layer on the pore surface. Then, the predicted dependencies of an attenuation α are:

$$\alpha \propto \frac{{\rho_f}^2\omega^2}{\eta} \qquad \text{in low frequency regime,}$$

$$\alpha \propto (\eta\rho_f\omega)^{1/2} \qquad \text{in high frequency regime.}$$

The observed frequency exponent is in between.

For a full characterization of the viscoelastic properties of this composite system, the attenuation of sound in aerogel itself is important. However, signal without helium could not be observed due to the large sound attenuation of aerogel. Xie and Beamish[11] observed that attenuation of dense aerogel with 84 and 89% porosity varies below about 40 K as $\alpha \propto \omega T^3$ and increased with porosity. To our knowledge there are no measurements of ultrasound attenuation with highly porous aerogel in the frequency region around 10 MHz at low temperatures. At room temperature, the attenuation in aerogel with porosity between 88 and 97% in the frequency range from 0.5 to 8 MHz was measured under ambient conditions[12]. The frequency dependence of attenuation changed from linear to quadratic with increasing porosity. In addition, the attenuation was varied by heat treatment, and was drastically reduced and did not show a significant frequency dependence after desorption of water. Thus, it is hard to estimate the

attenuation of our aerogel. The model of non-rigid SiO_2 skeleton will explain this experimental behavior.

Sound velocity and attenuation of liquid helium in 97% open aerogel were measured at the frequency of 6, 10, and 15 MHz. The measurements were thought to be in the low frequency or crossover regime, considering the characteristic length scale of our system and the experimental results. Velocity was lower than that in dense aerogels and didn't change with frequency. Attenuation has a frequency dependence with exponent about 1.1, which is between the high and low frequency limits of liquid in porous media. This should be useful information to elucidate acoustic properties of aerogel-helium system theoretically[13]. The anomalous attenuation in superfluid phase will be studied in near future.

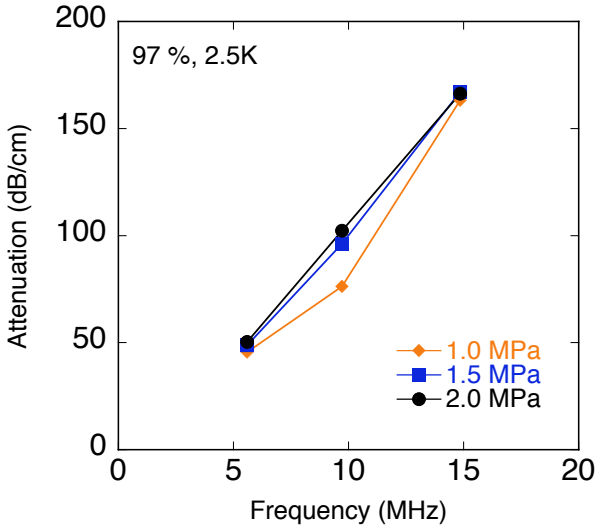


Figure 2. Sound attenuation for 97 % aerogel in normal phase as a function of frequency.

4. Acknowledgments

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