Acoustic properties of superfluid $^3$He in 97% aerogel

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Abstract. Superfluid $^3$He in silica aerogel provides a unique system for studying the effect of quenched disorder in the unconventional superfluid. We have performed longitudinal ultrasound (5.7 MHz) attenuation and sound velocity measurements of the superfluid $^3$He in 97% porosity aerogel. The attenuation and sound velocity were determined by direct propagation of sound pulses through the medium in a wide range of temperatures, down to 400 $\mu$K. The superfluid transition, marked by the increase in sound velocity, is substantially suppressed from that in 98% aerogel used in most of studies. The superfluid fraction determined from the sound velocity is less than 0.02 even at the lowest temperature.

1. Introduction

Liquid $^3$He is an ideal example of unconventional superfluid because it naturally eliminates impurities at low temperatures, which allows the study of the Fermi liquid in its purest form and then the $p$-wave Cooper pair state has been well understood. Silica aerogel, which is composed of silica strands of a few percent volume fraction, has been utilized to introduce impurity scattering in superfluid $^3$He which suppresses the superfluid transition temperature and the superfluid density [1]. The strand diameter is much smaller than the superfluid coherence length which is comparable to the mean strand distance and controlled by liquid pressure. Therefore, $^3$He superfluidity in aerogel provides a unique system for understanding the impurity effect in the unconventional superconductors. It has been predicted that superfluid $^3$He becomes gapless in the dirty limit in analogy with $p$-wave superconductors [2]. In fact, the gapless behavior has been experimentally observed by thermal conductivity [3] and heat capacity [4] measurements. The superfluid properties in aerogel can be varied from the almost clean to the very dirty limit by changing the pressure. The suppression of the superfluid transition temperature was small at the highest pressures, whereas superfluidity is suppressed completely at the lowest pressures [1]. As a result, there is a quantum phase transition at $p_c \approx 0.6$ MPa for 98% aerogel [5].

The acoustic properties of liquid $^3$He in aerogel are also affected by the presence of impurity scattering. The transition from first to zero sound in the normal liquid was found to be obscured by quasiparticle scattering [6]. Recent measurements using longitudinal ultrasound suggested the gapless superfluid by impurity scattering [7]. The structural correlation with aerogel is shown to play an important role in the behavior of superfluid $^3$He in aerogel [8]. Most of the studies in aerogel have been done with 98% porosity. Porosity of aerogel is just the starting point from which superfluid behavior can be understood. However, there are only a few studies using aerogels with low porosity [9, 10]. It is of interest to study the effect of the impurity with lower porosity. We have investigated the ultrasound properties of $^3$He in 97% aerogel.
Figure 1. Temperature dependence of the attenuation of longitudinal sound at 5.7 MHz for bulk $^3$He and $^3$He in 97% aerogel at 1.6 MPa. The attenuation at 14.6 MHz in 98% aerogel at 1.63 MPa [6] is also shown for comparison. $T_{c0}$ indicates the position of the bulk superfluid transition.

2. Experimental details
The aerogel with 97.0% porosity was synthesized by Matsushita Electric Works via a sol-gel process followed by hypercritical drying. Sample was cut into cylindrical shape with parallel ends, 7 mm in diameter and 2.0 mm in length. Two matched longitudinal LiNbO$_3$ transducers were mechanically pressed to the sample by a flat spring instead of gluing in order to avoid possible damage to the aerogel by the adhesive solvent. The transducers were maintained parallel by a copper spacer. Another acoustic cavity for bulk $^3$He was installed together into a copper cell. The sample cell was cooled using a dilution refrigerator, followed by copper adiabatic nuclear demagnetization. Temperature was determined by a $^3$He melting pressure thermometer and a Pt NMR thermometer. Pressure of $^3$He was measured by a capacitive strain gauge attached on the top of the sample cell.

Ultrasound measurements at the frequency of 5.7 MHz were made using a standard pulse transmission and phase sensitive detection technique. Two signals for bulk and in aerogel were obtained alternately using a switching circuit. The attenuation due to transducers and signal lines was calibrated from the sound signal of bulk liquid by using two identical sets of both the transducers and signal lines for bulk and aerogel. All signals were taken in the linear region where the amplitude of the received signal was proportional to that of excitation. In order to improve the signal to noise ratio, over several hundred signals were averaged. The resolution of the signal was within 10 ppm for changes in sound velocity. The absolute sound velocity was determined using the time of flight within about 2%.

3. Experimental results and discussions
The sound attenuation as a function of temperature both for bulk $^3$He and $^3$He in aerogel at 1.6 MPa is shown in Fig. 1. For comparison the attenuation at 14.6 MHz in 98% aerogel at 1.63 MPa [6] is also shown. The attenuation of bulk $^3$He represents a small peak due to pair breaking at the superfluid transition. The bulk transition temperature $T_{c0}$ and temperature
Figure 2. Temperature dependence of the sound velocity for $^3$He in 97% aerogel at 1.6 MPa and 3.2 MPa. $\Delta c$ is the velocity change from the normal fluid velocity $c_n$ at high temperatures. $T_{ca}$ indicates the position of the superfluid transition at 3.2 MPa.

dependence below $T_{c0}$ well agree to previous results, indicating that the liquid in the sample cell is enough cooled. The attenuation in 97% aerogel, however, doesn’t indicate the superfluid transition down to the lowest temperature, in contrast to that the attenuation drops rapidly below the aerogel transition $T_{ca} = 1.5$ mK in 98% aerogel.

The temperature dependence of the attenuation in 98% aerogel above $T_{ca}$ has been analyzed using the viscoelastic model modified with the contribution from aerogel-quasiparticle collisions [6]. Higashitani et al. has incorporated into the theory considering an additional contribution due to the momentum transfer from a quasiparticle to the elastic aerogel strand, followed by the motion of the aerogel itself together with liquid [11]. The weak temperature dependence above $T_{ca}$ observed in 98% aerogel [6, 12] is well described by the theory. On the other hand, the attenuation in 97% aerogel is almost constant except a small upturn, which has been observed also in 98% aerogel, around 100 mK. The result suggests that the motion of the aerogel is restricted and the normal fluid is strongly coupled to the aerogel.

The sound velocity in the normal state of liquid $^3$He in aerogel, $c_n$, is almost constant up to about 100 mK. The time of flight method gives $c_n = 281$ m/s and 364 m/s at 1.6 MPa and 3.2 MPa, respectively. These values in 97% aerogel are lower by about 14% than bulk. The temperature dependence of sound velocity around superfluid transition is shown in Fig. 2. The superfluid transition at 3.2 MPa has been observed as a rapid increase of the sound velocity. The transition temperature, $T_{ca} = 1.1$ mK, is strongly suppressed in comparison with 2.0 mK and 2.4 mK, respectively, in 98% aerogel and for bulk.

The coupling between the normal fraction of the superfluid $^3$He and the mass of the elastic aerogel modifies the conventional two-fluid hydrodynamic equations [13, 14]. In this consideration, the sound velocity of the fast longitudinal mode, $c_f$, in aerogel is given by $c_f = c_1 \sqrt{(1 + \rho_n \rho_s / \rho_n \rho) / (1 + \rho_a / \rho_n)}$, where $\rho_n(s)$ is the normal fluid (superfluid) density ($\rho = \rho_n + \rho_s$), $\rho_a$ is the aerogel density, and $c_1$ is the velocity of hydrodynamic sound in bulk $^3$He. The superfluid fraction determined from the sound velocity with this equation is less than 0.02 even at the lowest temperature, $T/T_{ca} \approx 0.4$, and is significantly suppressed from that in 98% aerogel.


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