Motion of $^3$He Quasiparticles in Aerogel Driven by Fourth Sound

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Abstract. While the shear viscous motion of the normal fluid component causes the energy loss of the fourth sound resonance in superfluid $^3$He confined in narrow pores, it is not yet clear what causes the energy loss of the fourth sound in the aerogel system. We prepared two aerogel samples of 99.0% and 97.5% porosities, which were directly grown in sintered silver sponges and performed the fourth sound resonance experiments. We found that the energy loss of the fourth sound resonance in aerogel is much smaller than that in pure liquid $^3$He, showing that the mean free path of $^3$He quasiparticles is strongly suppressed by aerogel strands. Such behavior is explained with the frictional flow. The temperature dependence of the frictional relaxation time will be discussed.

1. Introduction
Aerogel has been attractive because it is well-controllable impurity in the superclean system. Aerogel is made up of thin silica strands. The average distance between silica strands is comparable to the superfluid coherence length $\xi_0$, and the diameter of strands is much smaller than $\xi_0$. Thus the aerogel acts as an impurity for superfluid $^3$He. As a result, it has been measured by using various experimental methods[1, 2, 3] that the transition temperature $T_C$ and the superfluid fraction $\rho_s/\rho$ are strongly suppressed. We used the fourth sound resonance technique to investigate the transport properties of superfluid $^3$He in aerogel. In this work, we focus on the energy loss of the fourth sound resonance. The fourth sound is a compression wave of the superfluid component propagating through the narrow pore whose effective radius is so small that the motion of the normal fluid component is clamped by its viscosity. So the freely propagating fourth sound is non-dissipative. But the resonating fourth sound is able to drive the normal component slightly so as to maintain the total fluid density. This minute oscillation of the normal component causes the energy dissipation. We can drive the motion of the normal component and detect the energy loss simultaneously by using the fourth sound resonance. In pure liquid $^3$He (without aerogel), the motion of the normal component is well understood by the hydrodynamic theory including the slip effect[4, 5]; the energy loss of the fourth sound...
propagating in pure $^3$He confined in the narrow pore is represented as,

$$Q^{-1} = \frac{1}{4} \frac{\rho_n}{\rho_s} \left( \frac{R}{\delta_\nu} \right)^2 \left( 1 + \frac{4\zeta}{R} \right) \quad \text{(when } R \ll \delta_\nu \text{)}, \quad (1)$$

$$\delta_\nu = \sqrt{\frac{2\eta_n}{\rho_n\omega_m}} \quad (2)$$

where $\rho_n$, $R$, $\delta_\nu$, $\eta_n$, $\omega_m$ and $\zeta$ are the normal fluid density, the effective pore radius, the viscous penetration depth, the shear viscosity, the $m$-th resonance angular frequency $2\pi f_m$ and the slip length, respectively. Our previous results for pure $^3$He[6] agrees quantitatively with Eq.(1), and we obtained $R \sim 10 \mu$m. In this paper, we would like to verify whether or not this hydrodynamic theory is applicable to the aerogel system, and reveal the motion of the normal component in aerogel.

2. Experimental Details

We prepared sound resonators with the aerogel of 97.5% and 99.0% porosities, and without aerogel. We have grown the aerogel directly between the particles of sintered silver powders whose packing factor is 65%. The silver particles are almost spherical, with a diameter of about 70 $\mu$m. To confine the aerogel into sintered silver powder prevents the aerogel strands from oscillating together with liquid[7]. The resonator is cylindrical in shape, whose diameter is 8 mm, and the length $L$ is 15 mm. At each end of the resonator, a piezo electrode as a pressure transducer is attached so as to generate and detect a sound resonance. Measurements have been done by the conventional frequency spectroscopy technique. The $m$-th resonance frequency $f_m$ and the full width of half maximum $\Delta f_m$ for $m$-th resonance can be obtained by a Lorentzian fitting for frequency spectrum. The fourth sound velocity $C_4$, the superfluid fraction $\rho_s/\rho$, and the energy loss of fourth sound are calculated by well known formulae $C_4 = 2nL f_m/m$, $\rho_s/\rho = (C_4/C_1)^2$ and $Q^{-1} = \Delta f_m/f_m$ respectively. Here, $n \sim 1.4$ is the acoustic refraction index determined by the sound measurement using liquid $^4$He, and $C_1$ is the first sound velocity[8]. The measurement was performed in B-like phase at ambient pressure 28.9 bar and under zero magnetic field. The temperature was measured by a Pt-NMR thermometer located in bulk liquid.

3. Results and Discussions

The temperature dependence of superfluid fraction $\rho_s/\rho$ for the pure cell and two aerogel cells is shown in FIG. 1. In the lower porosity, $\rho_s/\rho$ and the transition temperature $T_C$, which is determined by extrapolating $\rho_s/\rho$ to zero, get lower; $T_C$ of each cell without aerogel (pure $^3$He) and with aerogel of 99.0% and 97.5% porosities are 2.43 mK, 2.27 mK and 1.76 mK, respectively. These results are qualitatively understood by IISM model[9], in which the suppression is determined by the number of impurities within the coherence length $\xi_0$. FIG. 2 shows the temperature dependence of the energy loss $Q^{-1}$ for 2nd mode. The energy loss of two aerogel cells are much smaller than that of the pure cell, and the energy loss does not depend on porosity except near $T_C$[10]. It means that Eq.(1) fails by introducing aerogel. The reasons are as follows; Eq.(1) shows that the energy loss $Q^{-1}$ is proportional to $\rho_n/\rho_s$ and $\delta_\nu^2$. First, ($\rho_n/\rho_s$)$_{aero}$ is larger than ($\rho_n/\rho_s$)$_{pure}$ due to the suppression of the superfluidity. And second, the shear viscosity $\eta_n$ is represented as $\eta_n = (1/5)np_k\lambda$, where $\lambda$ is the mean free path of the quasiparticle. $\lambda_{aero}$ becomes much smaller than $\lambda_{pure}$ due to the impurity scattering, so that $\delta_\nu^{aero}$ also becomes much smaller than $\delta_\nu^{pure}$. Therefore the energy loss in aerogel must be larger than that in pure liquid. However, we obtained the opposite results. The most possible interpretation for the suppression of the energy loss in the aerogel system is the collision drag.
effect[11]. Higashitani and Miura treated the propagation of the sound in superfluid $^3$He confined in the aerogel with the frictional drag force and evolved the dispersion relation of the sound. In the decoupling limit, in which the eigenfrequency of the elastic motion of the aerogel strands is much higher than the fluid oscillation, the energy loss of the fourth sound in the aerogel is derived to be

$$Q^{-1} = \frac{\rho_n}{\rho_s} \omega \tau_f,$$

where $\tau_f$ is the frictional relaxation time[12]. Using this formula, we obtained $\tau_f$ for each cell with aerogel, as shown in FIG.3. Although the energy loss does not depend on the porosity, $\tau_f$ turns out to be dependent on the porosity. Below $T/T_C \sim 0.6$, $\tau_f$ gets smaller with decreasing the temperature. The temperature and the porosity dependence of $\tau_f$ are qualitatively consistent with the numerical calculation[13]. Thus, in the aerogel system, the motion of normal fluid component is described by the frictional model, like Drude’s electron in the metal[14], rather than the viscous motion. However, further theoretical discussions are needed to interpret following complicated results: according to the Landau’s transport equation[15, 16], the frictional relaxation time $\tau_f(T_C) = (m/m^*) \tau$, where $m^*/m$ is the effective mass ratio that depends only on the ambient pressure[8], and $\tau$ is the impurity scattering time. If we extrapolate our $\tau_f$ to the transition temperature, we have obviously, $\tau_{99.0\%} < \tau_{97.5\%}$. Moreover, the transport mean free path $\lambda = v_F \tau$ becomes approximately a hundred times larger than the average distance between each strands, in aerogel.

4. Conclusion
We performed the fourth sound resonance experiments in two aerogel samples with different porosities at 28.9 bar. The energy loss of the fourth sound resonance in aerogel is much smaller than that of the pure liquid $^3$He, revealing the failure of the theoretical model which describes the pure system well. It causes the reduction of the viscosity that the strongly suppressed mean
The free path of $^3$He quasiparticle due to the scattering by the aerogel strands, and, as alternated, the contribution of the frictional force between them to the energy loss becomes dominant. The frictional relaxation time gets smaller with decreasing temperature. The temperature and porosity dependence of the frictional relaxation time $\tau_f$ qualitatively agree with the numerical calculation which take the frictional drag effect into account.

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