Superfluidity of $^{4}$He in dense aerogel studied using quartz tuning fork

K Matsumoto$^{1}$, R Okamoto$^{1}$, A Nakajima$^{1}$, S Abe$^{1}$
$^{1}$ Department of Physics, Kanazawa University, Kakuma-machi, Kanazawa 920-1192, Japan
E-mail: k.matsu@staff.kanazawa-u.ac.jp

Abstract. Superfluid $^{4}$He in aerogel is of interest because it has a normal component coupling to gel strand due to viscosity and a superfluid component with zero viscosity. Superfluid helium in aerogel has two sound modes, a slow critical mode and a fast one. In this study, quartz tuning fork was used in order to study acoustic properties of liquid $^{4}$He in aerogel with 90% porosity. Two pieces of aerogel were glued on both prongs of quartz tuning fork that had a resonance frequency of 33 kHz. The tuning fork was immersed in liquid $^{4}$He from 2 to 20 bar. The resonance frequency increased in the superfluid phase due to decrease in loaded mass. Temperature variation of resonance frequency was explained by that of superfluid density. Superfluid transition in aerogel was 2 mK lower than that without gel. Additional dissipation was observed in the temperature range between 1 K and transition temperature.

1. Introduction
Quartz tuning forks are piezoelectric mechanical oscillators consisted of two prongs and used as frequency standards for many devices with resonant frequencies typically in the kilohertz range. In recent years, quartz tuning forks have been used for the studies of quantum fluids such as viscosity[1, 2], turbulence[3, 4, 5], cavitation[6], coupling to acoustic modes[7, 8], and many others[9, 10]. The advantages of quartz tuning forks are highly sensitive, compact, and easy to install and operate. The $Q$ factors of quartz tuning forks are typically of order $10^5$ in vacuum at room temperature, and larger values can be attained at very low temperatures.

Acoustic property of superfluid helium is of interest because it has a normal component playing the role of viscous fluid and simultaneously a superfluid component with zero viscosity. The normal fluid in high-porous media like aerogel that is locked to the substrate by viscosity drags the substrate along. So, there are two sound modes, a slow critical mode and a fast one[11]. We have reported acoustic properties of liquid $^{4}$He in aerogel using longitudinal ultrasound and the different behavior from rigid porous material[12, 13]. An anomalous attenuation was observed in superfluid phase with 97% open aerogel at the frequency of 10 MHz[13]. Possibility of sound mode conversion was discussed in helium and porous material system[14]. In order to elucidate the acoustic properties in porous materials, it is useful to make measurements by changing the vibration frequency because coupling between aerogel and $^{4}$He could be changed by varying the viscous penetration depth.

We report our preliminary experiments on superfluidity of $^{4}$He in aerogel with 90% porosity using quartz tuning fork. In this study, quartz tuning fork that had a resonance frequency of 33 kHz in vacuum was used. The onset of superfluid transition was observed as an abrupt
increase in resonance frequency. Transition temperature in aerogel was 2 mK lower than that without gel. This suppression of transition temperature was consistent with other aerogels. Temperature variation of resonance frequency was explained by that of superfluid density. Additional dissipation was observed in the temperature range between 1 K and transition temperature.

2. Experimental procedures
Experiments were made using commercially available tuning fork (DT-38, Daishinku cooperation) which had a resonance frequency of 32,768 Hz at room temperature in vacuum. The arm of the tuning forks had length 3.03 mm and a rectangular cross-section of thickness 0.336 mm and width 0.474 mm shown in Fig. 1. The metal can was removed.

Two pieces of aerogel with 90% porosity were glued on the front surfaces of both prongs with Stycast 2850FT as shown in Fig. 1. Each piece had similar size but the shape wasn’t identical because of difficulty in cutting the aerogel. The total volume of aerogel was about $8 \times 10^{-12}$ m$^3$.

The tuning fork was located in a copper cell that contacted with the mixing chamber of a dilution refrigerator. Temperature was measured with a RuO$_2$ resistance thermometer. Pressure of the cell was measured and regulated using a pressure sensor located at room temperature. In our experiment we have measured the resonance frequency and amplitude as well as the resonance line width of the quartz tuning forks using a standard Lock-in amplifier circuit. Resonance was kept track during temperature variation by adjusting oscillator frequency automatically with a computer algorithm of phase locked loop. Wide frequency sweep across the resonance peak was made at some fixed temperatures. The excitation of oscillation has been done with small amplitude of the signal. So, the response of the tuning fork was in linear region.

![Figure 1. Photograph of quartz tuning fork with aerogel. The aerogels were shown in ellipses.](image)

3. Results and discussion
3.1. Resonance frequency
The resonance frequency with aerogel decreased to 32.1635 kHz in vacuum at room temperature due to the mass of aerogel and Stycast. Resonance frequency of tuning fork with aerogel $f_w$ was measured as functions of liquid helium pressure at 0.14, 1.3, and 3.0 K. At all temperatures, resonance frequency decreased linearly with helium density. That without aerogel $f_{w/o}$ also linearly depended on helium density.

Resonance frequencies in vacuum for both without aerogel $f_{w/o}^{vac}$ and with aerogel $f_{w}^{vac}$ showed negligible temperature dependence compared with those in liquid helium. Upper panel of Fig. 2 shows the resonance frequency change of the tuning fork with aerogel from that at 2 K in vacuum. In liquid helium at 20 bar, $f_w$ and $f_{w/o}$ had a minimum $f_{w}^{min} = 31.0105$ kHz and $f_{w/o}^{min} = 31.6772$ kHz at superfluid transition temperature $T_\lambda$, respectively. Lower panel of Fig. 2 shows $f_w$ and $f_{w/o}$ as functions of temperature. In this panel, vertical axis is plotted as the resonance
frequency difference $\delta f$ from $f^{\text{min}}$ for with and without aerogel such as $\delta f_{w/} = f_{w/} - f_{w/o}^{\text{min}}$ and $\delta f_{w/o} = f_{w/o} - f_{w/o}^{\text{min}}$. Frequency change $\delta f_{w/}$ and $\delta f_{w/o}$ agree with each other in normal phase. But, those significantly differ in superfluid phase. In superfluid phase, increase in resonance frequency with aerogel is larger than that without aerogel because large amount of helium decoupled from the aerogel strand. Figure 3 shows the ratio of frequency change $|f_{w/o}^{\text{vac}} - f_{w/o}^{\text{vac}}|$ with aerogel $f_{w/o}$ and without aerogel $f_{w/o}$ at 20 bar. $|f_{w/o}^{\text{vac}} - f_{w/o}^{\text{vac}}|$ corresponds to frequency change by filling helium at transition temperature. $|f_{w/o}^{\text{vac}} - f_{w/o}^{\text{vac}}|$ and $|f_{w/o}^{\text{vac}} - f_{w/o}^{\text{vac}}|$ at lowest temperature decrease about 6 and 8.5% from transition temperature, respectively. Resonance frequencies at lowest temperature didn’t decrease to $f^{\text{vac}}$ for both with and without aerogel case.

![Figure 2](image-url) **Figure 2.** Resonance frequency of quartz tuning fork with and without aerogel at 20 bar. That with aerogel in vacuum is also represented in upper panel. The solid line is the fitting to the without aerogel data.

![Figure 3](image-url) **Figure 3.** Temperature dependence of the ratio of frequency change $|f^{\text{vac}} - f_{w/o}^{\text{vac}}|$ for with and without aerogel. The solid line is the fitting to the without aerogel data.

In order to analyze resonance frequency, we use the theoretical relation by R. Blaauwgeers[1]. The resonance frequency $f$ is represented as follows,

$$ T > T_{\lambda} : \left(\frac{f^{\text{vac}}}{f}\right)^2 = 1 + \frac{\rho}{\rho_0} \beta + B \frac{S}{V} \rho q \sqrt{\frac{\eta \rho n}{\pi f}}. $$

$$ T < T_{\lambda} : \left(\frac{f^{\text{vac}}}{f}\right)^2 = 1 + \frac{\rho}{\rho_0} \beta + B \frac{S}{V} \rho q \sqrt{\frac{\eta \rho n}{\pi f}}. $$

Here $f$ and $f^{\text{vac}}$ are resonance frequencies in liquid helium and vacuum. $\eta$, $\rho$ and $\rho_0$ are viscosity coefficient, density and normal density of helium. $\rho_0$ is density of quartz. $S$ and $V$ are surface area and volume of a prong of tuning fork. $\beta$, $B$ are fitting parameters.

$f_{w/o}$ was well fitted with $\beta = 0.971$ and $B = 1.0$ in both normal and superfluid phase as shown in solid lines in Fig. 2 and 3. From this fitting, the second term ($\frac{\rho}{\rho_0} \beta$) in Eq. 2 due to potential flow is dominant in comparison with the third term ($B \frac{S}{V} \rho q \sqrt{\frac{\eta \rho n}{\pi f}}$) due to viscous drag.
When viscous drag effect (third term) dominantly contributed, the frequency ratio \( \frac{f_{w/o} - f_{w/o}^w}{f_{w/o} - f_{w/o}^{min}} \) will decrease to nearly zero because \( \rho_o \) becomes zero at lowest temperature.

\( f_{w/} \) was well fitted in normal phase with the parameters close to the case without aerogel (\( \beta = 1.108 \) and \( B = 1.0 \)). However, it was hard to fit \( f_{w/} \) in superfluid phase using the same parameters. Large increase in \( f_{w/} \) in superfluid phase was attributed to the mass decoupling of superfluid \(^4\)He in aerogel. Normal fluid in aerogel is considered to coupled to aerogel strand, comparing strand separation with viscous penetration depth. However, quantitative analysis of superfluid component is difficult because of the low accuracy of gel volume and dominant potential flow contribution. Then, we estimated temperature dependence of superfluid component in aerogel as follows. Resonance frequency had linear dependence on liquid density. The resonance frequency changed about 0.3% at the lowest temperature from that at transition temperature. So, it is considered that the frequency difference between with and without aerogel \( (\delta f_{w/} - \delta f_{w/o}) \) is proportional to the superfluid component in aerogel. Temperature dependence of \( \delta f_{w/} - \delta f_{w/o} \) agreed with that of superfluid fraction of bulk helium as shown in Fig. 4. This suggests that superfluid fraction in aerogel of this study had the same temperature dependence as that of bulk.

Figure 4. Resonance frequency difference \( \delta f_{w/} - \delta f_{w/o} \) as a function of temperature compared with superfluid density.

Figure 5 shows resonance frequency in 20 bar expanded around superfluid transition. Superfluid transition was recognized as onset of increase in resonance frequency. Transition temperature in our aerogel decreased 2 mK which was in reasonable agreement with suppression of superfluid transition in other gels.

Figure 5. Resonance frequency of quartz tuning fork with and without aerogel at 20 bar around superfluid transition.
3.2. Resonance line width
The resonance width of tuning fork $\Delta f$ with aerogel increased to 4.44 Hz in vacuum at room temperature due to additional mass and dissipation of Stycast and aerogel. $\Delta f$ decreased to 1.29 Hz at 1.3 K in vacuum. In resonance tracking measurements, we evaluated $\Delta f$ from resonance frequency $f$ and amplitude of the signal $A$ as $2\pi f^2 F_f A$, the driving force $F$ was evaluated from excitation voltage and properties of our tuning fork. Figure 6 shows resonance width without aerogel $\Delta f_w/o$ at 20 bar. $\Delta f_w/o$ is almost constant in normal phase and begins to decrease rapidly at superfluid transition. Figure 7 shows resonance width with aerogel $\Delta f_w$ at 20 bar. $\Delta f_w$ also shows small temperature dependence in normal phase and rapid decrease in superfluid phase. $\Delta f_w$ (Fig. 7) was larger than $\Delta f_w/o$ (Fig. 6) in both normal and superfluid phase. Large scatter of $\Delta f_w$ was observed in superfluid phase. Acoustic modes such as second sound is possible to couple to the fork resonance. For example, large jump in $f_w$ and $\Delta f_w$ were observed at 1.3 K. For this reason, we made frequency sweeps at some fixed temperatures. $\Delta f_w$ obtained by frequency sweep was represented as squares in Fig. 7 and coincide reasonably with that by tracking measurement.

We used the theoretical relation by R. Blaauwgeers[1] in order to analyze resonance width. The resonance width $\Delta f$ is represented as follows,

$$
T > T_\lambda : \quad \Delta f = \frac{1}{2} \sqrt{\frac{\rho_0 f}{\pi}} C \frac{S}{m_{vac}} (\frac{f}{f_{vac}})^2,
$$

$$
T < T_\lambda : \quad \Delta f = \frac{1}{2} \sqrt{\frac{\rho_0 f}{\pi}} C \frac{S}{m_{vac}} (\frac{f}{f_{vac}})^2,
$$

where $m_{vac}$ is effective mass of the prong, $C$ is a fitting parameter. We neglected resonance width in vacuum $\Delta f_{vac}$ because this was small compared with $\Delta f$ in liquid helium.

![Figure 6. Resonance width of quartz tuning fork without aerogel $\Delta f_w/o$ at 20 bar. The solid line is the fitting.](image1)

![Figure 7. Resonance width of quartz tuning fork with aerogel $\Delta f_w$ at 20 bar. Those obtained frequency sweep are shown as squares. The solid line is the fitting.](image2)

$\Delta f_w/o$ at 20 bar was well fitted in both normal and superfluid phase by the above equations and fitting parameter $C = 0.70$ as shown the line in Fig. 6. $\Delta f_w$ in normal phase was well fitted with $C = 0.96$ as shown the line in Fig. 7. However, $\Delta f_w$ doesn’t agree with that from Eq. 4.
in superfluid phase. Temperature variation of $\Delta f$ is expected to result from $\sqrt{\rho n}$. This implies that additional dissipation occurred between 1 K and $T_c$ in superfluid phase. We have observed anomalous sound attenuation in similar temperature region using several MHz ultrasound[13]. For further study on the acoustic properties of liquid $^4$He in aerogel, it is necessary to make experiments at various frequencies and with other aerogels.

4. Summary
We reported our preliminary experiments on superfluidity of helium in aerogel with 90% porosity using quartz tuning fork with the frequency of 33 kHz. Superfluid transition temperature in our aerogel decreased 2 mK, which was in reasonable agreement with suppression of superfluid transition in other gels. Temperature variation of resonance frequency was explained by that of superfluid density. Additional dissipation was observed in the temperature range between 1 K and transition temperature.

Acknowledgments
This work was supported by JSPS KAKENHI. We thank Dr. K. Kanamori and Dr. K. Nakanishi at Kyoto University for providing aerogel. We thank K. Nunomura for technical assistance.

References
[1] Blaauwgeers R, Blazkova M, Clovecko M, Eltsov V B, de Graaf R, Hosio J, Krusius M, Schmoranzer D, Schoepe W, Skrbek L, Skyba P, Solntsev R E and Zmeev D E 2007 J. Low Temp. Phys. 146 537-62
[2] Bradley D I, Fear M J, Fisher S N, Guénault A M, Haley R P, Lawson C R, McClintock P V E, Pickett G R, Schanen R, Tsepelein V and Wheatland L A 2009 J. Low Temp. Phys. 156 116
[3] Bradley D I, Fear M J, Fisher S N, Guénault A M, Haley R P, Lawson C R, Pickett G R, Schanen R, Tsepelein V and Wheatland L A 2014 Phys. Rev. B 89 214503
[4] Ahlstrom S L, Bradley D I, Clovecko M, Fisher S N, Guénault A M, Guise E A, Haley R P, Kolosov O, McClintock P V E, Pickett G R, Poole M, Tsepelein V and Woods A J 2014 Phys. Rev. B 89 014515
[5] Jackson M J, Kolosov O, Schmoranzer D, Skrbek L, Tsepelein V and Woods A J 2016 J. Low Temp. Phys. 183 208
[6] Blažkova M, Chagovets T V, Rotter M, Schmoranzer D and Skrbek L 2008 J. Low Temp. Phys. 150 194
[7] Rysti J and Tuoriniemi J 2014 J. Low Temp. Phys. 177 133
[8] Schmoranzer D, LaMantia M, Sheshin G, Gritsenko I, Zadorozhko A, Rotter M and Skrbek L 2011 J. Low Temp. Phys. 163 317
[9] Bradley D I, Clovecko M, Fisher S N, Garg D, Guénault A M, Guise E A, Haley R P, Pickett G R, Poole M and Tsepelein V 2013 J. Low Temp. Phys. 173 750
[10] Todoshchenko I, Kaikkonen J P, Blaauwgeers R, Hakonen P J and Savin A 2014 Rev. Sci. Instrum. 85 085106
[11] McKenna M J, Slaweci T and Maynard J D 1991 Phys. Rev. Lett. 66 1878
[12] Nishikawa M, Yoshino K, Abe S, Suzuki H, Matsumoto K, Tayurskii D and Tajiri K 2005 J. Phys. Chem. Solids 66 1506
[13] Matsumoto K, Tsuboya H, Yoshino K, Abe S, Suzuki H and Tayurskii D 2007 J. Low Temp. Phys. 148 615
[14] Brusov P, Parpia J M, Brusov P and Lawes G 2001 Phys. Rev. B 63 140507