

Study of superfluid ^3He films with a micro-electro-mechanical device

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Abstract. A micro-electro-mechanical system (MEMS) device with a $1.25\ \mu\text{m}$ gap between a movable plate and the substrate was immersed in superfluid ^3He and cooled below $500\ \mu\text{K}$ at 21.2 bar. Mechanical resonances of its shear motion were monitored on warming from the base temperature. Our preliminary results demonstrate increasing damping and decreasing resonance frequencies with temperature, consistent with a thermal damping model caused by thermal quasiparticles. The quality factor (Q) of the oscillator remains surprisingly low ($Q \approx 30$) down to $0.2T/T_c$, about 4 orders of magnitude smaller than the value in vacuum at 4 K. The average superfluid gap was determined to be significantly suppressed from the value in bulk at the corresponding pressure.

1. Introduction

In the normal state, liquid ^3He – an almost ideal Fermi liquid – possesses the full symmetry that a condensed matter system can possibly have. Below around 2 mK, the system enters into unconventional *p-wave* spin-triplet superfluid phases where all of the symmetry except for translational symmetry is broken, exhibiting extraordinarily rich physical phenomena. The surface scattering in unconventional superfluids/superconductors induces quasi-particle bound states and suppresses the order parameter near the surface within the coherence length, often called Andreev surface bound states (ASBS). This generic nature of unconventional superfluid order parameter near the boundaries combined with the exotic symmetries in the superfluid phases of ^3He [1] lends an unfathomable source of fascinating physical phenomena [2–8] predicted to exist in confined geometry, many of which are of topological origin. Superfluid ^3He in confined geometry is indeed a treasure box that only a few groups have just started to probe experimentally [9, 10].

Various types of mechanical oscillators such as vibrating wires [11] and tuning forks [12] have been employed with great success to investigate bulk superfluid ^3He and also as reliable low temperature thermometers. In order to study quasi-two-dimensional liquid ^3He , we have developed comb-drive micro-electro-mechanical systems (MEMS) devices consisting of a movable center plate suspended by serpentine springs over a substrate with a well defined gap [13, 14]. When such a device is immersed in the liquid, a well defined film is formed naturally in the gap. The center plate of the device can be actuated to oscillate in its own plane (shear motion), exhibiting a resonant behavior from which one can extract physical properties of the surrounding fluid.



In superfluid $^3\text{He-B}$ with an isotropic gap, the mean free path of quasiparticles increases exponentially with decreasing temperature, and it could become much larger than the size of the experimental devices, placing the fluid-probe system in the ballistic limit. In this regime the hydrodynamic concepts cease to work, and the damping of the oscillators can be described by a simple model [15]. When an oscillator is driven at a small velocity, the damping force is proportional to the velocity. The damping coefficient decreases rapidly with temperature as $\exp(-\Delta_0/k_B T)$, where Δ_0 is the bulk energy gap and k_B is the Boltzmann constant [16]. In this work, we report our preliminary results of the resonance properties of a MEMS device submerged in superfluid ^3He : the temperature dependences of the resonance frequency and the damping of the oscillator in $^3\text{He-B}$ at 21.2 bar.

2. Experiment

The detailed descriptions on the design and the operation of the MEMS device employed in this study can be found in [14,17]. A differential capacitance method was used to detect the resonance motion of the MEMS device which has a movable poly-silicon plate with $200 \times 200 \mu\text{m}^2$ size and $2 \mu\text{m}$ thickness. The gap between the plate and substrate is $1.25 \mu\text{m}$. The device was immersed in liquid ^3He and cooled down to the base temperature of about $500 \mu\text{K}$ at 21.2 bar by a dilution refrigerator and a copper demagnetization stage. The system was let to warm up naturally from the base temperature during which multiple resonance spectra of the resonator were obtained by sweeping the excitation frequency through the resonance. Temperature was measured by a ^3He melting curve thermometer (MCT) above 1 mK and a platinum NMR thermometer below 1 mK which was calibrated against the MCT. In order to operate the Pt NMR thermometer, the ^3He sample was exposed to a magnetic field of 14 mT perpendicular to the plane of the film. Temperature was measured right before and after each frequency sweep to monitor possible heating during the sweep and the average of the two measurements was used to represent the temperature for the sweep. No appreciable heating was observed for all the data presented in this work.

The displacement of the oscillating plate is the solution to the equation of motion of a damped driven harmonic oscillator. Due to the phase shift of the background signal with frequency in the experiment, the amplitude of the output was used to fit to the Lorentzian, x_a , after a proper background subtraction:

$$x_a = \frac{A f_0 d}{\sqrt{(f_0^2 - f^2)^2 + (df)^2}}, \quad (1)$$

where $A = F_0/(4\pi^2 m f_0 d)$ is the amplitude of the Lorentzian, F_0 the amplitude of the driving force, m the mass of the oscillator, d the full width at half maximum (FWHM), f the excitation frequency, and f_0 the resonance frequency in vacuum. Here A , f_0 , d are fitting parameters and f is swept through the resonance frequency. The width d is proportional to the damping coefficient experienced by the oscillator assuming a linear velocity dependence of damping force, while the resonance frequency f_0 can be related to the fluid loading to the resonator:

$$\gamma = 2\pi d m_{total}, \quad (2)$$

$$k = 4\pi^2 m_{total} f_0^2, \quad (3)$$

where γ is the damping coefficient F_{damp}/v , m_{total} the resonator mass plus the loading mass, k the spring constant of the MEMS device which was measured at 4 K in vacuum.

3. Results and Discussion

The amplitudes of the resonance at various temperatures are shown in Fig. 1. From the base temperature to about 1.3 mK where the liquid is still in superfluid state, the spectrum evolves

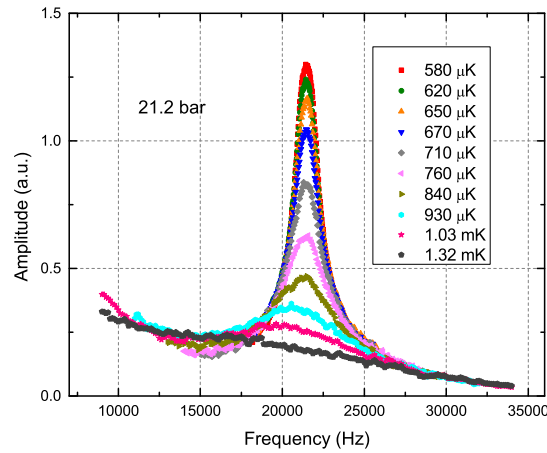


Figure 1. Temperature evolution of resonance spectra of the MEMS device at 21.2 bar with a constant excitation of $1.0 V_{pp}$.

progressively from a well defined Lorentzian to a very broad hump. The width of the resonance increases rapidly as the temperature rises, indicating a fast growth of damping force. Meanwhile, the peak position shifts to lower frequencies due to the fluid mass loading to the resonator.

To understand the temperature dependence of damping force, two important length scales need to be evaluated and compared. One is the mean free path, l , of the quasiparticle which increases exponentially with decreasing temperature due to the isotropic energy gap. The other is the characteristic length, a , of the apparatus, which is related to the dimensions of the movable plate of the MEMS device in this case. The characteristic length of the MEMS device is of the order of the plate size $a \approx 200 \mu\text{m}$. When l is much less than a , the system is in the hydrodynamic regime where the temperature dependence of the fluid viscosity, along with the geometry of the device, determines the damping force. An effort has been made to obtain the temperature dependence of the viscosity of normal ^3He through the damping force on a similar MEMS device, which will be published elsewhere.

On the other hand, when l is much greater than a , the system goes into the ballistic regime where the hydrodynamic concepts break down. For $T \lesssim 0.4 T_c$, l becomes larger than a typical length scale of MEMS devices [18]. The damping force exerted on the MEMS device can be formulated through a model where scattering of thermal quasiparticles off the moving object is considered [15]. The model includes a key feature in superfluid, Andreev scattering of low-lying quasiparticles. When the object moves slowly, the velocity dependence simplifies to a linear relationship. The coefficient of proportionality, which is directly related to the FWHM through Eqn.(2), thus has a temperature dependence solely from the density of quasiparticles $\propto \exp(-\Delta_0/k_B T)$. Therefore, the width of the peak has a temperature dependence $d \propto \exp(-\Delta_0/k_B T)$ [11].

The resonance was fitted to Eqn. (1) to extract d , A , and f_0 . The FWHM d are plotted against the reduced temperatures T/T_c for four excitations in Fig. 2. At the lowest temperature the peak width is still around 700 Hz, which is about 4 orders of magnitude larger than that in vacuum at 4 K. This indicates that the damping force at this temperature is still much larger than the intrinsic damping arising from the internal dissipation of the resonator. The fact that these four sets of data agree with each other demonstrates the damping coefficient is independent of driving force or resonator velocity, *i.e.*, the resonator is in the linear regime. A fit of the

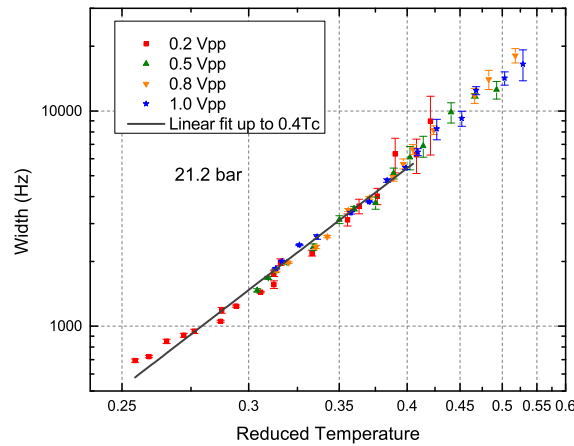


Figure 2. Temperature dependance of FWHM for various excitations. The y -axis scale is logarithmic while the x -axis scale is reciprocal. The straight line is the result of a fit of the data below $0.4 T/T_c$ to $d \propto \exp(-\Delta_0/k_B T)$ [11].

data below $0.4 T/T_c$ to the exponential dependence gives $\Delta_0 = 1.57 k_B T_c$, which is about 20% smaller than $1.85 k_B T_c$, the bulk gap at 21.2 bar [19]. Although it is needed to have a direct determination of T_c , the observed suppression of the gap is substantial but expected considering the suppression of the order parameters due to the boundaries of the film [20]. Reaching a lower base temperature is essential to verify the exponential temperature dependence of the damping to the intrinsic damping limit and also to extract a more accurate gap value [11].

The peak amplitude A and resonance frequency f_0 are plotted against the reduced temperatures for four excitations in Fig. 3. The left panel shows that the normalized amplitudes lie upon each other, ensuring the response of the oscillator is linear with the driving force. However, nonlinearity was observed when the resonator velocity exceeded a certain critical value, where excess damping set in and the lineshape was deformed from the Lorentzian. The amplitude decreases as temperature rises until around $0.4 T/T_c$, where the amplitude seems to saturate. The right panel of Fig. 3 demonstrates the resonance frequency remains almost constant for $T < 0.4 T/T_c$ before it starts to decrease at higher temperatures. This crossover occurs around the same temperature where the system enters into the hydrodynamic regime on warming. In the ballistic regime where damping is caused by direct momentum transfer between the quasiparticles and the resonator through scattering, the damping force is in phase with the velocity and no shift in resonance is expected [16]. Nevertheless, the low temperature limit resonance frequency, 21450 Hz, is about 100 Hz lower than in vacuum at 4 K. At this moment it is difficult to isolate the contributions from the fluid film only to the temperature dependences of the width, amplitude and position of the resonance peaks. A new design of the device is proposed so that the properties of films could be determined exclusively.

4. Conclusions

A MEMS device with a $1.25 \mu\text{m}$ gap has been immersed in superfluid ^3He and cooled down to $500 \mu\text{K}$. Its resonance properties were measured on warming and resonance parameters such as peak width, amplitude and position were obtained as functions of temperature. The peak width is directly related to the damping coefficient and does not depend on velocity in the linear regime. Crossover from hydrodynamic to ballistic regime with decreasing temperature was observed in

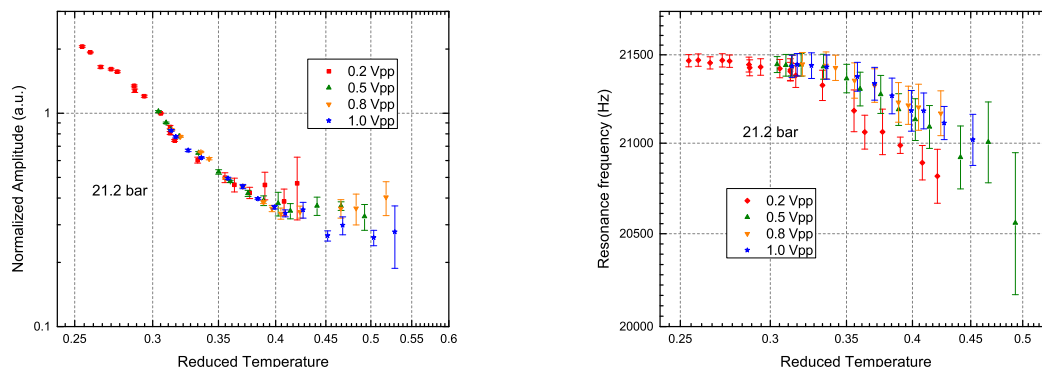


Figure 3. Log-log plots of temperature dependence of amplitude and resonance frequency for various excitations. Left panel: normalized amplitude of resonance peak against reduced temperature where fitted peak amplitudes are normalized with corresponding excitations; Right panel: resonance frequency against reduced temperature.

the temperature dependence of the resonance frequency. The temperature dependence of the width below $0.4T/T_c$ gives an energy gap of $1.57 k_B T_c$ which is substantially smaller than the bulk value at the corresponding pressure. The peak amplitude also shows a significant change in its temperature dependence at a higher temperature, $0.4T/T_c$.

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