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Decoupling of Confined Normal ^{3}He

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Abstract Anodic bonding was used to fabricate a 10 mm diameter × 640 nm tall annular geometry suitable for torsion pendulum studies of confined ^{3}He. For pure ^{3}He at saturated vapor pressure the inertia of the confined fluid was seen to be only partially coupled to the pendulum at 160 mK. Below 100 mK the liquid's inertial contribution was negligible, indicating a complete decoupling of the ^{3}He from the pendulum.

Keywords ^{3}He · Normal liquid · Slip

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1 Introduction

Experiments on ^{3}He films on highly polished silver have revealed novel information on the momentum transfer from a smooth surface to quasiparticles. Casey *et al.* constructed a torsion pendulum in which two polished coin silver surfaces were separated in height by a 50 µm diffusion-bonded copper washer. They observed that films of pure ^{3}He adsorbed on the top and bottom surfaces (varying in thickness from 100 nm to ≈ 300 nm) decoupled from the oscillator at a thickness dependent temperature below 60 mK [1]. Earlier experiments on pure ^{3}He (<100 ppm ^{4}He) confined between two polished silicon slabs [2], separated by a ≈ 35 µm Kapton washer, showed a temperature dependent slip. Many experiments [2, 3] reveal that a

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^{4}He coverage, sufficient to form a superfluid layer, changes the boundary condition at the ^{3}He-solid interface toward specular, thus altering the transfer of momentum across the solid-liquid interface. In our present experiment, the geometry was chosen to allow observation of the alteration of the superfluid phase diagram by confinement [4–6]. However, even without any ^{4}He coverage the ^{3}He fluid was observed to decouple in the normal state, precluding observation of superfluidity.

2 Experimental Details

The details on the construction of the cell will be published elsewhere [7]. The torsion head consisted of a 640 nm deep × 10 mm outer diameter, 4 mm inner diameter circular cavity nanofabricated into a 3 mm thick, 17 mm square silicon piece that was anodically bonded [8] to a 3 mm thick Hoya SD-2 glass sheet [9]. The silicon was epoxied to a coin silver torsion rod that had drive and detect electrodes epoxied to the central moment of inertia. The bonding scheme was different from that used by Rhee *et al.* [10] because we wanted to avoid the use of potentially texture-altering supporting posts that were thought to be necessary for strength in silicon-oxide-silicon bonded cells. The torsion rod was driven and detected in its antisymmetric resonant mode, and the frequency and Q recorded continuously as the temperature was swept between 160 mK and 0.9 mK. A schematic of the torsion oscillator is shown in Fig. 1. The calculated moment of inertia of the torsion head was 2.06 g-cm^2, while the contribution of the liquid ^{3}He in the cavity, at 0 bar, was 5.0×10^{-7} g-cm^2. The expected shift in the frequency due to the coupling of ^{3}He, $\Delta f_{expected}$ is 156 μHz. At the antisymmetric torsion mode frequency (1287 Hz) the viscous penetration depth exceeds the cavity height at all temperatures. Thus we expect that the helium should be well coupled to the torsion head.

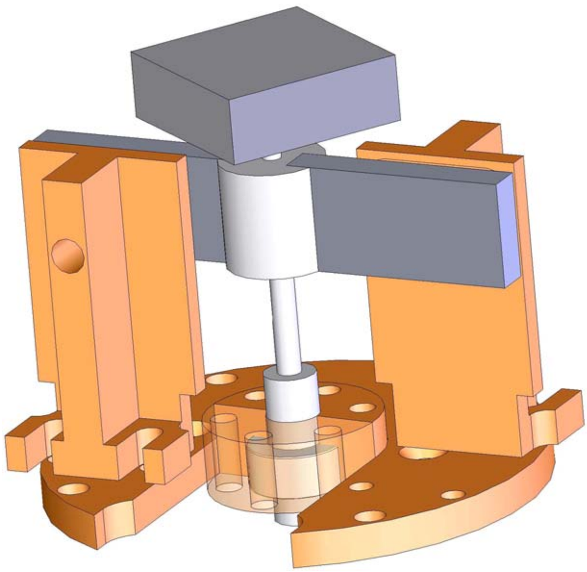

Fig. 1 (Color online) Schematic of the torsional oscillator cell. The silicon-glass head (topmost element) was epoxied to the coin silver torsion rod. The two electrodes (rectangular structures) were epoxied to a central moment of inertia, and together with closely spaced copper electrodes comprise the capacitive drive and detect elements. The torsion rod is a hollow fill line connected to the sintered silver heat exchanger via an indium o-ring seal

3 Results

In Fig. 2, we show the temperature dependent frequency shift of the empty cell and of the cell filled with ^{3}He at saturated vapor pressure. We note that the full cell has a small additional decrease in frequency between 160 mK and 100 mK compared to the empty cell frequency which we attribute to the entrained mass of ^{3}He. After fitting the empty cell background $f_{fit}(T)$ (see Fig. 2 (top)) we calculate the frequency shift $\Delta f = f_{fit}(T) - f_{full}(T)$ and form the ratio $\Delta f/\Delta f_{expected}$, the fraction of liquid inertia coupled to the head, and plot this in Fig. 2 (lower). The dissipation change on filling was too small to be resolved in this experiment.

The decoupling observed by Casey *et al.* [1] was understood in terms of an internal friction model along the lines of Meyerovich and Stepaniants [11]. The model developed the idea of a characteristic momentum transfer time, τ, that was related to a phenomenological friction time, $\tau_F = \hbar/(2E_F)$, where E_F is the Fermi energy; the quasiparticle collision time, τ_η; the ratio of the characteristic roughness height, l, to the correlation length, R; the Fermi wavevector, k_F; and the characteristic film thickness, d;

$$\frac{1}{\tau} = 3\left(\frac{1}{\tau_F \tau_\eta}\right)^{1/2}\left(\frac{l}{R}\right)^2 \frac{1}{k_F d}. \quad (1)$$

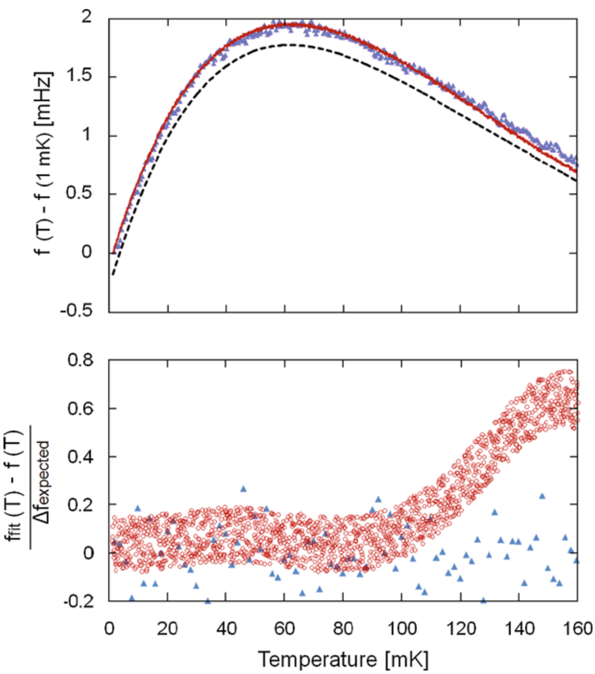

Fig. 2 (Color online) *Top*: Resonant frequency, $f(T) - f(1\text{ mK})$ ($f(1\text{ mK}) = 1286.4788$ Hz) as a function of temperature. The data with small scatter is for the filled oscillator (*red* online); *solid triangles* (*blue* online) are for the empty cell. The frequency offset is the same for both. The *dashed curve* is a fit to the empty cell data with the expected frequency shift $\Delta f_{expected} = 156$ μHz subtracted off. The frequency would be expected to follow this line if all the liquid inertia were coupled to the torsion head at all temperatures. *Bottom*: The measured frequency shift $f_{fit}(T) - f(T)$ normalized by $\Delta f_{expected}$. The *open circles* are for the filled oscillator (*red* online) and the *solid triangles* (*blue* online) show the scatter of the empty cell data around the fit

The characteristic time τ related the fraction of inertia coupled to the cell to the inertia of the fluid, m, the cell inertia, M, and the operating frequency, ω by

$$\frac{\Delta f}{f} = -\frac{m}{2M(1+(\omega\tau)^2)}. \quad (2)$$

In our present experiment, we find the roughness of the silicon to be unresolved using a scanned AFM, while the glass displays a roughness height of 2.5 nm. Due to features of the surface structure, we find values for the correlation length to range from 138 nm to as high as 220 nm [7, 12] in some directions. From these results and values of the quasiparticle scattering time from Greywall [13] we find $\omega\tau = 1$ at ≈ 60 mK for $R = 138$ nm (presumably the roughest *i.e.* short correlation length dominates). The fact that we see mass decoupling well above this temperature may indicate that the model cannot account for momentum transfer when the surface roughness is small. Unfortunately the epoxy silicon-to-silver joint failed in a routine warm up before extensive fill and emptying and pressure-dependent measurements could be carried out. Certainly measurements of the decoupling with a larger fluid-to-torsion head inertia and better resolution surface scans are necessary to reach a definite conclusion.

4 Conclusions

In order to measure the mass coupled to the torsion pendulum, and carry out measurements on the superfluid phases we will have to further understand the role of surface roughness on momentum transfer. We intend to better characterize the surface roughness of the glass and silicon that comprise the cell walls, perhaps using small angle x-ray scattering. We also will examine a less confined cell geometry *e.g.* 1 μm tall, with thinner cell walls to improve the ^{3}He-to-cell moment of inertia ratio, and also compare momentum transfer by polished and etched surfaces where the ratio of l to R may be altered and well-characterized.

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