

Torsion pendulum studies of thin ^3He slabs

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Abstract

A high precision torsional oscillator has been developed for the detection of two dimensional superfluidity in ^3He films of thickness comparable to the superfluid coherence length, 70 nm at $T = 0$. The mass loading from such a film can be detected with a 0.1% resolution. Measurements on normal films show an unexpected de-coupling from the surface with decreasing temperature, below 60 mK. The frequency shift and dissipation data can be interpreted using a phenomenological interfacial friction model.

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1. Introduction

The flow of fluid past a surface is a fundamental hydrodynamic problem of some longevity, yet the behaviour of the boundary layer and surface slip remain questions under active investigation for classical fluids [1]. Attempts to determine the viscosity of quantum liquids have required correction for these effects. Torsional oscillator studies of liquid ^3He in contact with highly polished surfaces or surfaces covered by a ^4He film, have also produced a number of unexplained results [2].

In this paper we report preliminary results for the viscous coupling between a polished metal surface and a thin ^3He film. We explore a completely new flow regime, in which the viscous penetration depth $\delta = (2\eta/\rho\omega)^{1/2}$ is much larger than the film thickness at all temperatures. An attractive feature of this quantum fluid, as opposed to usual classical fluids, is that the mean free path is strongly temperature dependent, and can greatly exceed the thickness of the film at low mK temperatures. Thus

in some sense we can say that, in this regime, the entire film constitutes a “boundary layer”.

2. Torsional oscillator

The torsional oscillator developed for this work [3] is fabricated from coin silver to reduce its temperature dependent background. The working surfaces of the oscillator are mechanically polished to a roughness better than 10 nm and diffusion bonded together by a copper gasket. The “head” of the oscillator is linked to a coin silver body by a coin silver tube acting as torsion rod and fill line. The antisymmetric mode of the head and body is at 2842 Hz, with a low temperature Q of order 10^6 . The oscillator frequency can be determined to better than 1 part in 10^9 , corresponding to the inertial contribution of a 0.1 nm thick film. This is achieved by driving the oscillator at fixed frequency, close to resonance, and measuring the in-phase and quadrature response. A low drive level ensures that the effects of non-linearity are negligible. The helium film can be loaded into the oscillator by heating the fill line to 800 mK while the oscillator is held at 500 mK. The nominal film thickness is inferred from the shift of

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oscillator period due to mass loading, measured at 60 mK, and the calculated moment of inertia of the oscillator head.

3. Results and discussion

Thus far the properties of normal films of nominal thickness 137 and 328 nm have been studied. The results for the period shift and dissipation due to the film, obtained after a subtraction of the temperature dependent background are shown in Fig. 1, where all data were taken during slow temperature sweeps. At high temperatures we find a period shift approximately independent of temperature, which we attribute to full mass loading. As the temperature is decreased the behaviour of the period shift indicates a de-coupling of the film in both cases. This is accompanied by an increase in dissipation, and for the thicker film we observe a clear dissipation maximum.

This experiment probes the transfer of transverse momentum between the ^3He quasiparticles and the surface. Since $\delta \gg d$, a simple phenomenological model consists in treating the film as a rigid slab, frictionally coupled to the surface. The frictional force is taken to be proportional to the velocity difference of the surface and liquid slab, with coefficient η . A characteristic relaxation time can be defined in terms of this friction coefficient and the mass density of the film, via $\eta = \rho/\tau$. Solving the coupled equations of linear motion of an oscillator and liquid slab of mass M and m , respectively, it can be shown that the period shift and dissipation due to frictional coupling to the slab are given by

$$\frac{\Delta P}{P} = \frac{m}{2M} \frac{1}{1 + \omega^2 \tau^2} \quad \text{and} \quad \Delta Q^{-1} = \frac{m}{M} \frac{\omega \tau}{1 + \omega^2 \tau^2}$$

By taking the ratio of ΔQ^{-1} and $\Delta P/P$, we find that the present data are consistent with $\tau \propto 1/T$. The dissipation maximum corresponds to $\omega \tau = 1$. Microscopically, considering the substrate as subject to random transverse forces $f(t)$ due to impacts by quasiparticles, this result implies that the time integral of the autocorrelation function $\langle f(0)f(t) \rangle$ is independent of temperature.

The figure shows fits to the data, assuming $\tau = A/T$. The period shift as $T \rightarrow 0$ indicates that some part of the film remains locked to surface, possibly by surface roughness; we include this effect in the fits by an additive

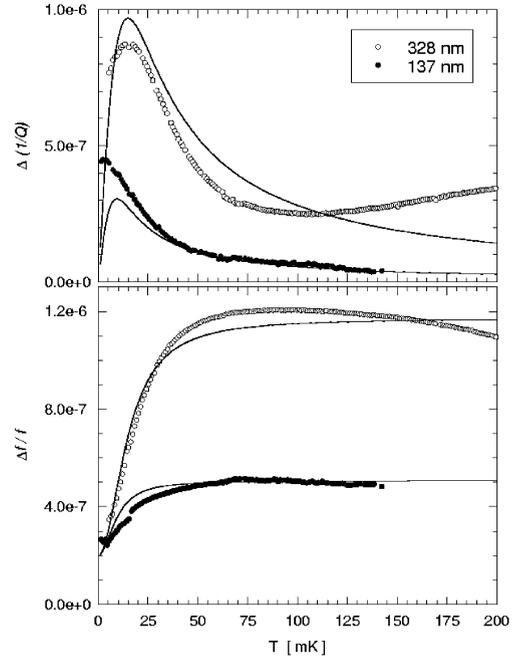


Fig. 1. Frequency shift and dissipation due to film.

constant in the expression for the period shift. Clearly the model can qualitatively reproduce the dissipation maximum observed for the thicker film. Future measurements will seek improvements in the quality of data and background subtraction, as well as attempts to detect the superfluid transition in these films.

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