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Torsion Pendulum for the Study of Thin ^{3}He Films

G. W. Morley, A. Casey, C. P. Lusher, B. Cowan,
J. Saunders, and J. M. Parpia

Royal Holloway University of London, Egham, Surrey TW20 0EX, UK

We report on the design of a torsion pendulum that can resolve the mass loading from 5×10^{17} ^{3}*He atoms (equivalent to a 1000Å film) with a 0.1% resolution. The oscillator is fabricated from coin silver alloy, and the working surfaces are two highly polished coin silver discs, each with well-characterized surface roughness, that are diffusion welded together using a copper gasket. We report on the cell's temperature dependent background. The cell will be used to examine the evolution of the superfluid density and transition temperature as a function of film thickness as well as the normal fluid behavior.*

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Studies of ^{3}He films whose thickness is on the order of the coherence length[1–3] have revealed that there is likely to be novel physics when the characteristic thickness is reduced to the order of the coherence length. It is known from both experiment[4,5] and theory[6–9] that confinement of ^{3}He to a restricted geometry can lead to an alteration of the phase diagram from that observed in the bulk. This regime is also worthy of exploration because earlier experiments on films produced conflicting results that have yet to be resolved. The first experiment[1] with a torsion pendulum on metastable ^{3}He films, showed evidence for a phase transition when the film thickness was reduced below 2750Å. In third sound measurements[3], the inferred ρ_s appeared to have a qualitatively different temperature dependence for the thinnest films. Flow experiments[2] carried out over a number of years show that there is a special need for care in preparation of the sample surfaces. There are also unresolved questions about the behavior of normal ^{3}He in contact with ^{4}He covered surfaces[10,11] and new ground to be explored in the ballistic regime in the normal phase where the quasiparticle mean free path

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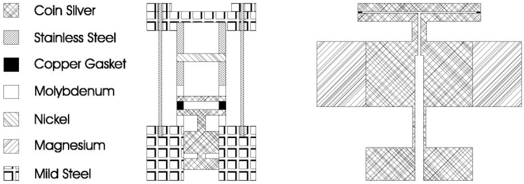

Fig. 1. On the left we show a schematic (not to scale) of the jig used to diffusion weld the coin silver cap, a 50 μm thick polished copper gasket, and the coin silver body together. A 10 μm thick molybdenum foil was inserted to prevent adhesion of the silver to the steel. On the right, a schematic rendition of the torsion pendulum showing the head, cavity, and magnesium wings. The oscillator is 21 mm tall, and the head diameter is 15 mm.

can exceed the film thickness by many orders of magnitude.

A stable film of well-established and controllable thickness is clearly desirable as it would permit measurements over a wide range of temperatures. The films would have to be loaded into a high-stability device with well-characterized surfaces to provide adequate mass resolution. It is also desirable to allow for the thickness to be varied continuously (as opposed to confinement between plates of fixed separation). These criteria could be met by a double torsion oscillator of Andronikashvili-Reppy design fabricated from coin silver. This alloy was selected because of the small temperature dependence[12,13] of its elastic constant and dissipation as compared to beryllium-copper[12,14]. We report here on the construction, operation and the temperature dependent background that we have measured.

The working surfaces that would be wetted by the helium are confined to the "head" of the torsion pendulum. The body of the torsion pendulum was separated from the head by a torsion element that also functioned as the fill tube. Magnesium electrodes that electrostatically drive and detect the motion of the pendulum were epoxied (stycast 2850) to the body with cigarette paper spacers. The body was coupled to the foot of the pendulum assembly by a second torsion tube. Two torsional and a "floppy" mode of oscillation could be excited. The two torsion modes were a symmetric mode at 500Hz (in which the body and head move in-phase with one another) and an antisymmetric mode at 2842Hz (in which the head and body move in opposition). The floppy mode at 341Hz corresponds to the "swaying" of the body and head about the point of attachment of the lower torsion tube to the foot. The device, shown schematically in Fig. (1) is oriented with the "head" as the lowest point. In order to follow the hydrodynamics of the film, we examined the antisymmetric torsion mode of the oscillator.

To reduce ambiguities in mass loading we elected to cool the confined helium film through the polished silver surfaces alone. We note that the surface to volume ratio for a 1000Å film is comparable to that for a conventional silver sinter. The silver surface of the oscillator then must also be in sufficiently good thermal contact with the nuclear stage so that a moderate thickness film ($\leq$ 4000Å) can be cooled to well below 1 mK. The helium film can be loaded onto the oscillator by heating the fill line to 800 mK while maintaining the oscillator at 500 mK. Once the film is loaded, the fill line is cooled, and the resulting heat leak to the helium should be negligible.

The construction of the oscillator required that details of two important steps had to be completely resolved before the oscillator could be assembled. The first was to obtain a high degree of smoothness and flatness of the surfaces, and the second was to achieve a successful bond between the oscillator body and the cap that would contain the helium sample.

The silver surfaces were prepared by attaching them to a 32 mm diameter brass sleeve compatible with a Buehler MiniMet1000 device and polishing with carbide followed by a series of diamond suspensions. A Tencor profilometer as well as phase contrast microscopy reveal that the surfaces have a characteristic roughness better than ±100 Å over a 50μm length scale.

The oscillator body and the flat disc, that together constituted the working cavity of the viscometer, had to be separated by a gasket, thin enough (50 μm thick) to ensure that the upper and lower films are of nearly equal thickness Fig.(1). The gasket and the two coin silver surfaces had to also be leak tight, as well as providing for thermal contact. These criteria were met by selecting copper as the gasket material and by joining the two coin-silver surfaces to the copper with a diffusion weld. The efficacy of a diffusion weld can be improved by the application of pressure and the elevation of the working temperature at which the diffusion weld is carried out. Because silver and copper form a eutectic, the diffusion of the copper into the silver alloy can be enhanced by carrying out the weld just below the eutectic temperature. The fact that the copper and coin silver have nearly identical thermal expansion coefficients is also beneficial. The coin silver discs had a diameter of 15 mm, and the copper gasket was 50 μm thick, with a 15 mm outer and a 14mm inner diameter. The assembly was clamped together using two M2.5 stainless screws tightened to 0.5 Nm torque. A 0.5 mm thick nickel disc was also inserted in the stack (Fig. (1)) to moderate the pressure (nickel has a smaller expansion coefficient than stainless, while silver has a larger expansion coefficient). The jig was heated to 755^0C in vacuum and held there for 50 minutes. The resulting joint was leak tight and showed minimal distortion of the silver surfaces. A similar process has been previously reported between a single coin silver and copper surface[13].

The oscillator was mounted to an additional copper torsional isolator

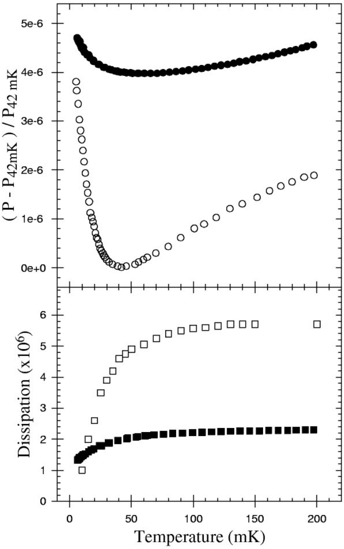

Fig. 2. In the top panel, we show the temperature dependence of the change in the period relative to the value at 42mK for the coin silver (solid circles), and beryllium-copper (open circles) oscillators[14]. Below we show the temperature dependence of the dissipation of the coin silver (solid squares), and beryllium-copper (open squares) oscillators[14].

that acted as a low-pass filter. This was levelled to better than 0.1^0 accuracy using a travelling microscope. Fixed electrodes were placed within 50 μm of the magnesium electrodes to form the drive and detector capacitors, and these were anchored (together with the coaxial cables) to the isolator. The magnesium electrodes were biased at 100 V through a separate coaxial line.

In order to minimize the noise introduced by active drive components such as a phase locked loop[15], we elected to drive the oscillator at a fixed frequency close to its resonance. We could accurately determine ($\leq 0.1^o$) the phase angle between drive and detect signals by calibrating the response of the oscillator at a fixed temperature. The measurement also provided a reference value for the Q, Q_R, and amplitude at resonance, A_R. The resonant frequency and dissipation (Q^{-1}) could be obtained by selecting the frequency that gave a null response of the in-phase signal, and recording the frequency and amplitude, or by driving the resonator at a fixed frequency, f_D, (and

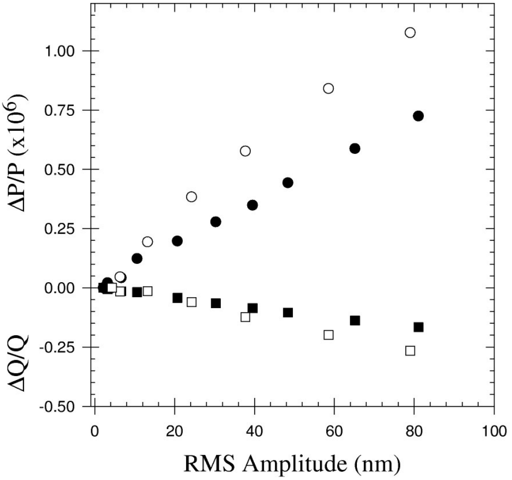

Fig. 3. We show the amplitude dependence of the period shift(in ppm) observed at 1.36K (solid circles) and at 10mK (open circles), for this coin silver oscillator. We also show the amplitude and temperature dependence of the reduction of the Q (solid squares – 1.36K, open squares – 10mK).

drive) and measuring the quadrature, X_T, and in-phase, Y_T, response.

$$Q_T = \frac{X_T^2 + Y_T^2}{X_T}\left(\frac{Q_R}{A_R}\right) \tag{1}$$

$$f_T = f_D\left(1 + \frac{Y_T}{X_T}\frac{1}{2Q_T}\right) \tag{2}$$

The resonant frequency f_T and Q_T could be determined from Eqs. (1,2) even though f_D may fall well outside the half-width of the resonance. The dissipation and period shift of the oscillator together with the behavior of a beryllium copper oscillator[14] are plotted in Fig. (2).

It is well known that the period and dissipation of mechanical resonators can exhibit a strong temperature dependence[16] and non-linear behavior at even modest amplitudes[17]. Two approaches can be followed in order to minimize the nonlinearity, the first being to drive the oscillator at a sufficiently small drive so that the non-linear behavior is small, and the second being to maintain the oscillation at a constant amplitude. Our drive method can, in principle, operate at a constant amplitude by varying the drive voltage. For simplicity we operate the oscillator at a constant (low) drive level. The temperature and amplitude dependence are shown in Fig. (3).

The frequency stability of the oscillator under temperature regulation is found to be better than $\pm 1\mu$Hz/10h. Thus the frequency can be resolved to better than 1 part in 10^9. Since the combined inertia of two (equal thickness) 1000Å ^{3}He films is calculated to be 6.14×10^{-7} gcm^2, and the inertia of the torsion pendulum head is 0.87 gcm^2, the noise corresponds to the inertial contribution from a 1Å thick film. Put differently, the mass sensitivity of the pendulum is better than 5×10^{14} atoms.

In summary, we have constructed and characterized the operational behavior of a coin silver torsion pendulum. The device should allow the exploration of the superfluid ^{3}He phase diagram, and the hydrodynamics of normal ^{3}He films on the order of 1000Å thickness with adequate mass resolution over a temperature range below 200mK.

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