Physica B 169 (1991) 521-522
North-Holland

LOW TEMPERATURE EXPONENTIAL AND LINEAR FREE DECAY OF THIRD SOUND RESONANCES

F. M. Ellis and H.Luo

Department of Physics, Wesleyan University, Middletown, Connecticut, 06457 USA

Low temperature free decays of third sound resonances show weak exponential attenuation at low amplitudes. A variety of behaviors has been observed at high amplitudes including stronger exponential decays and occasional linear decays. The flow velocities characteristic of the onset of these non linear effects are typically 1cm/s. Pinned vortices appear to play a major role in the damping.

Third sound (1) in superfluid ^{4}He films propagates as both a thickness and temperature oscillation. The dominant restoring force for these surface disturbances is the Van der Waals attraction of the helium film to the substrate. The mechanically significant fluid motion, on the other hand, is parallel to the substrate when the wavelength (~1cm in this work) is much longer than the film thickness (1.5nm–7.5nm) making the wave motion essentially equivalent to an A.C. film flow. Thermal oscillations accompanying the wave motion lead to dissipation through thermal relaxation at warmer temperatures. At low temperatures, more complicated forms of dissipation take over as the thermal energy becomes less influential (2).

We have studied low temperature dissipation through the free decay of third sound resonances. The resonator design has previously been used for driven resonance scans (3). It is constructed from two silvered glass slides held 8.6μm apart by epoxy glue. The glue forms the outer perimeter of a circular cavity in which the helium film is adsorbed. One of the plates is partitioned into electrodes which are used to drive and detect the resonances. Non–silvered surfaces constitute less than 1% of the resonator area.

Third sound modes are excited by electrostatic forces resulting from up to 20Vpp applied to the drive plate. The resulting thickness oscillations are detected capacitively on the pickup plate. The drive is then removed and the thickness oscillations are synchronously tracked down to an amplitude limit determined by microphonic noise or the integration time of the lock–in detection electronics. This integration time is limited by the rate of the free decay to be measured. The free decays show no noticeable dependence on the drive–up history.

Figure 1 shows two log–amplitude vs. time decays which illustrate features typical of moderately thick films at low temperature. The amplitude scale is obtained directly from the geometry of the pickup electrode and is defined so that $\eta(r,\phi)=\delta h J_m(k_{nm}r)\cos(m\phi)$ describes the film thickness oscillation at frequency $\omega=C_3k$. The corresponding flow velocity and lateral fluid element displacements are then easily found from the equations of motion. Figure 1(a) is the m=1, n=1 mode at a third sound velocity of C_3=10m/s followed for almost three decades in amplitude. The sharp dips are changes in the lock–in amplifier gain and integration time. The low amplitude exponential behavior begins at about δh=4pm corresponding to a peak flow velocity of .44cm/s and a peak lateral displacement of 1.5μm. Figure 1(b) is the m=3, n=1 mode at C_3=8m/s. Its low amplitude exponential behavior begins at δh=20.5pm corresponding to a peak flow velocity of 1.4cm/s and a peak lateral displacement of 1.9μm. Defining the quality factor, Q, locally in terms of the slope, figure

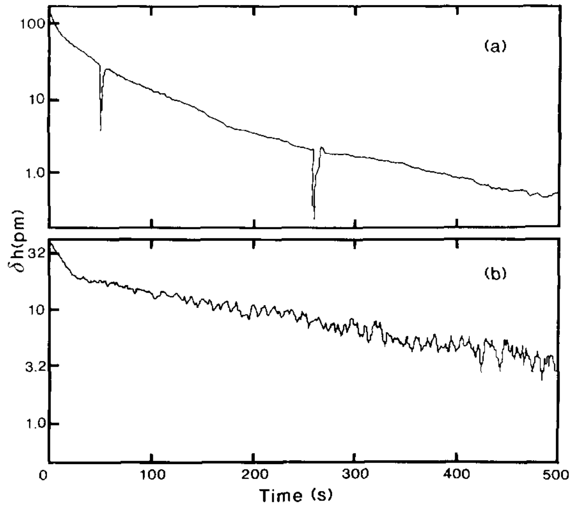

Figure 1
Third sound free decays at 60 mK for the m=1 (a) and the [m=3] (b) modes. The third sound velocity is 10m/s [8m/s]. The maximum flow velocity is 20cm/s [2.4cm/s] at the beginning of the decays. These decays are typical of moderately thick films – 4.4nm [5.0nm].

1(a) changes fairly gradually from about Q=40000 at high amplitudes to 450000 at low amplitudes. Figure 1(b) shows an abrupt change from a Q of 94000 at high amplitudes to 680000 at low amplitudes.

In general, the qualitative forms of figure 1 remain the same for temperatures below .5K and thicknesses greater than 2nm. Several factors, however, impede a routine investigation of the dissipation as a function of these parameters. Most important, it should be noted that the dissipation in this regime is quite small. Low amplitude Q's range from 30000 to 800000. It is therefore easy for small energy loss mechanisms to influence the observed damping. This makes the damping mildly erratic with film thickness and not reproducible from one resonator to the next. Also, the Q's could sometimes be up to 40% different for geometrically split mode pairs where the frequency and wavelength of the third sound is essentially identical. This indicates that some of the energy is being lost in a specific position in the resonator, influencing each mode differently.

Occasionally, there were specific thicknesses where the decays changed in a qualitative way, sometimes drastically. Figure 2 shows a free decay plotted as log–amplitude vs. time (a) and linear amplitude vs. time (b). This form of decay was observed at a third sound velocity of 5.1m/s at 60mK. As it decays, it is dissipating energy equivalent to a simple friction force of 1.3×10^{-9}N/m². Similar features, though usually less prominent, were commonly observed in thicker films (C_3 < 12m/s) and occasionally in thinner films. These features almost always fall in the region between the high and low decay rates discussed earlier. Careful

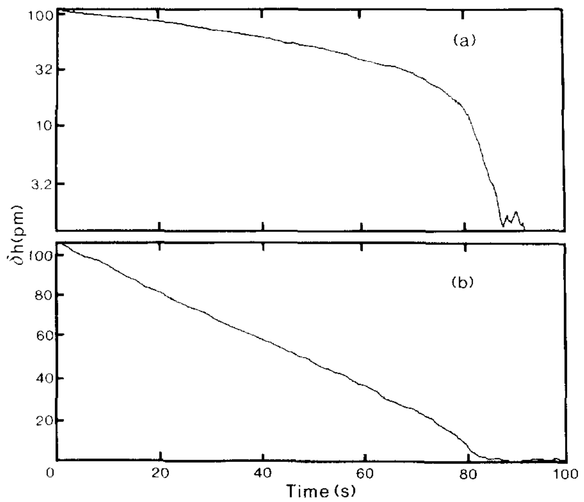

Figure 2
This shows an anomalous decay plotted with a logarithmic (a) and linear (b) amplitude scale. An effective friction–like force with the substrate of 1.3×10^{-9}N/m² would be needed to cause this decay.

consideration of figure 1(a) reveals a small example of this in the vicinity of 10pm. Another important characteristic is that these features appear and disappear with changes in film thickness as small as 1%.

We propose that the damping observed in all cases is associated with the presence of pinned vortices. The pinning and depinning of vortices is an important element in the decay of persistent currents at warmer temperatures (4). At low temperatures, pinned vortices would introduce several possible damping mechanisms, both responding to the third sound wave via the Magnus force. As the wave moves by, the superfluid in the vicinity of the vortex oscillates laterally, resulting in an oscillating force. The vortex would then move with its pinned end either stationary or dragging over a limited range. Energy would be transferred to the normal fluid excitations either through the two–dimensional analog of mutual friction (5), or the drag process (6). The size of these effects can be estimated from bulk experiments and require pinned vortex densities in the range of 10^3/cm² to 10^5/cm² to result in decays typical of figure 1.

Many of our observations have possible explanations based on pinned vortex damping. The amplitude dependences come about as more vortices participate in dragging with the increased Magnus force. Estimating the Magnus force at amplitudes in figure 1 where the low amplitude behavior begins gives a drag force roughly 1.5×10^{-4} to 2.0×10^{-4} times the vortex line tension at the above vortex densities. The mode differences and the differences from cell to cell can be attributed to slight differences in substrate properties, and hence pinning characteristics. Finally, linear amplitude decays may be due to resonant coupling of single vortices to the third sound mode, perhaps in regions of capillarity.

We wish to acknowledge Wesleyan University for its support of this work.

REFERENCES

(1) S. J. Putterman, Superfluid Hydrodynamics (North–Holland, Amsterdam, 1974) Ch.V

(2) W. F. Saam, and M. W. Cole, Phys. Rev., B11, 1086 (1975)

(3) F. M. Ellis, and H. Luo, Phys. Rev., B39, 2703 (1989)

(4) D. A. Browne, and S. Doniach, Phys. Rev., B25, 136 (1982)

(5) C. F. Barenghi, R. J. Donnelly, and W. F. Vinen, J. Low Temp. Phys., 52, 189 (1983)

(6) P. W. Adams, M. Cieplak, and W. I. Glaberson, Phys. Rev., B32, 171 (1985)