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M. Bagley, P. Main, J. Hook, D. Sandiford, H. Hall. DIRECT OBSERVATION OF ORBITAL DISSIPATION AND SUPERFLOW COLLAPSE IN $^3\text{He-A}$. Journal de Physique Colloques, 1978, 39 (C6), pp.C6-13-C6-14. 10.1051/jphyscol:1978606 . jpa-00217498

HAL Id: jpa-00217498

<https://hal.science/jpa-00217498>

Submitted on 1 Jan 1978

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DIRECT OBSERVATION OF ORBITAL DISSIPATION AND SUPERFLOW COLLAPSE IN $^3\text{He-A}$

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Résumé.— Des expériences de pendule de torsion dans lesquelles le temps de relaxation orbitale est comparable à la période d'oscillation montrent une atténuation fortement dépendante de l'amplitude dans $^3\text{He-A}$ qui est absente dans $^3\text{He-B}$. A forte amplitude, la densité superfluide apparente tend vers zéro, suggérant l'effondrement du courant superfluide comme l'ont décrit Bhattacharyya, Ho et Mermin.

Abstract.— Torsion pendulum experiments in which the orbital relaxation time is comparable with the oscillation period show strong amplitude dependent damping in $^3\text{He-A}$ that is absent in $^3\text{He-B}$. At large amplitudes the apparent superfluid density decreases towards zero, suggesting collapse of superflow as described by Bhattacharyya, Ho and Mermin.

In our previous torsion pendulum experiments /1,2/ on superfluid ^3He the width d of the flow channel was such that the relaxation time of the orbital texture $\tau = (\mu/\rho_s)(2md/W)^2$ was very much longer than the period of oscillation. In these circumstances we observed an essentially static texture controlled by the mean square relative velocity, $(v_s - v_n)^2$.

With the object of observing dynamic textures and the concomitant dissipation by orbital viscosity, we have reduced d so that the orbital relaxation time is of the same order as the period of oscillation. The construction of the torsion pendulum is essentially as described previously, but the CMN pill is now surrounded by a stack of 25 toroidal flow channels, each of which is 49 μm in height and 0.75 mm in radial extent. The channels were formed by casting Stycast 1266 around aluminium foil and etching away the aluminium after machining was completed.

As before, the oscillation amplitude was controlled by a feedback loop, and the drive level was used as a measure of damping. To facilitate the measurement of absolute amplitudes a capacitance bridge (GR 1621) operating at 10 kHz was used to detect the oscillations, and the suitably phase-shifted output at the pendulum frequency (about 60 Hz) was used to trigger the drive voltage. In this self-oscillating mode the oscillation frequency could be read continuously on a frequency counter. Our basic experimental data are thus additional resonance width and frequency shift relative to the normal state; both are of the order of mHz. All the

measurements were carried out at the pressure of the melting curve minimum (29.7 bar) to avoid pressure fluctuations.

Figure 1 shows two recorder traces of drive level as a function of time during the final stages of demagnetisation and the subsequent warmup. The only difference is that in figure 1(a) the liquid remained in supercooled A-phase throughout, whereas in figure 1(b) it entered the B-phase. It is clear that at this amplitude (though not at the lowest amplitudes) there is a substantial excess damping in the A-phase but not the B-phase; this alone is strongly suggestive of dissipation by orbital viscosity. The small hydrodynamic damping in the B-phase is attributable to normal shear viscosity. Another feature worthy of note in figure 1(b) is that when the liquid returns to the A-phase the dissipation builds up to its full value only rather slowly and in a somewhat erratic manner.

Both damping and frequency shift are roughly proportional to $(1 - T/T_C)$. We therefore show in figure 2, as a function of velocity amplitude at $(1 - T/T_C) = 0.1$, the values of these quantities, normalised to the low amplitude frequency shift. Two features are noteworthy:

- (1) the damping maximum, suggesting that we pass through the condition $\omega\tau \sim 1$ as the amplitude increases;
- (2) the great reduction in frequency shift at large amplitudes (which was not observed in the B-phase), implying that the whole liquid is tending to follow the motion of the pendulum.

The second observation, taken together with the slow and erratic return of dissipation after

a $B \rightarrow A$ transition, strongly suggests that we are observing the collapsed superflow described by Bhattacharyya, Ho and Mermin /3/ ; the delayed return of damping would be associated with the difficulty of surmounting the free energy barrier to formation of the collapsed state.

Fig. 1 : Recorder traces of damping as a function of time at an amplitude of 3.0 mm/s during the final stages of demagnetisation and the subsequent warmup. In (a) the liquid remained in supercooled A-phase, whereas in (b) it entered the B-phase.

We therefore compare our results with numerical solutions of the equation of motion proposed by Hall /4/

$$\left(\frac{\alpha\hbar}{2m}\right)^2 \nabla^2 (\bar{v}_s - v_n) = (\bar{v}_s - v_n)^3 + \frac{\beta\mu}{\rho_s} \frac{\partial \bar{v}_s}{\partial t}, \quad (1)$$

with the boundary conditions $\bar{v}_s = 0$ at the walls and $v_n = v_0 \sin \omega t$ everywhere. From the solution we compute the rate of change of momentum and hence the torque on our torsion pendulum.

Fig. 2 : Normalised frequency shift δv_s (solid points) and extra resonance width δv_w (open points) as a function of velocity amplitude v_0 . The curves are computed from eq. 1 with $\alpha^2 = 2.5$ and $\beta = 2.0$.

The full curves in figure 2 are calculated for $\alpha^2 = 5.0$ and $(\beta\mu/\rho_s) = 1.2 \times 10^{-4} \text{ cm}^2 \text{ s}^{-1}$, which with the measured value of μ /5/ gives $\beta = 4.0$. These parameters give about the best overall fit ; larger values fit the low amplitude damping better, and smaller values fit the high amplitude frequency shift better.

In view of the considerable oversimplification involved in using the single parameter $\bar{v}_s$ to describe changes in supercurrent resulting from the effect of textures on v_s , ρ_s , and curl $\mathbf{l}$, we consider that eq. (1) describes our results as well as can reasonably be expected. Certainly, the agreement over the general form of the results give us considerable confidence that the ideas of superflow collapse and orbital relaxation on which eq. (1) is based are essentially correct.

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