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PHASE-SLIPS IN THE FLOW OF SUPERFLUID ^{4}HE THROUGH A SUBMICRON ORIFICE

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We have constructed a 6 Hz Helmholtz oscillator to study phase-slip phenomena in superfluid ^{4}He.This method was pioneered by Zimmermann (1-2) and by Avenel and Varoquaux (3-6). A superconducting displacement transducer employing a D.C. SQUID and capable of resolving a displacement of 2×10^{-13} m in one second is used. We report preliminary flow studies at 0.3K using a slit with cross-sectional dimensions of $0.4\mu \times 4.6\mu$ and 0.08μ length. We detect sudden dissipation events, the smallest being consistent with phase-slips of 2π .

1. INTRODUCTION

An understanding of phase coherence properties and the microscopic processes leading to dissipation and onset of critical flow in a superfluid has been of fundamental interest to physicists for nearly four decades.It is believed that when the critical flow rate is reached in a channel the phase of the complex order parameter should slip resulting in a well defined loss of flow energy (7).

If a singly quantized vortex line traverses the entire flow channel, the phase will slip by 2π. However, phase changes of any arbitrary size can, in principle, be produced by either partial or full traverses by several lines.

If phase slips are to be used as a tool to study macroscopic phase coherence, one presumably needs to create a situation in which reproducible and empirically predictable phase slips occur. Zimmermann (1) has suggested that the most favorable geometry for such events would be a small channel with effective length and width well below one micron (8).

In an apparatus meeting the above criterion, Avenel and Varoquaux (AV) have observed highly reproducible,discrete transitions corresponding to phase-slips of 2π (3-4). The reproducibility of these slips, combined with quantization of circulation and a high degree of phase coherence has led them to produce staircase patterns analogous to those in an rf SQUID (5-6).

This paper reports the first attempts in Berkeley to reproduce the features seen by AV with the long-term goal of understanding the phase slip mechanisms and exploiting the quantum phase coherence to create a sensitive detector of rotation (9).

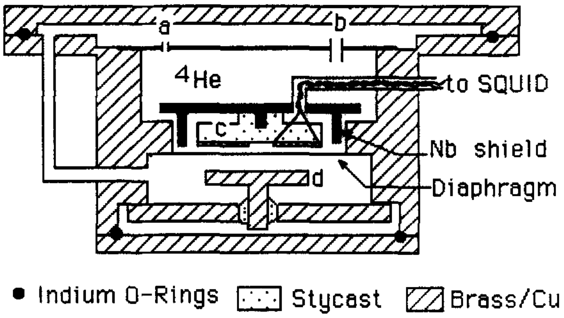

Figure 1. Experimental Cell

2. APPARATUS

Our Helmholtz resonator, shown in Fig. 1, is generically similar to that of AV. The small flow channel (a) is a slit of dimensions $0.43\mu \times 4.63\mu$ made with e-beam lithography in an 80nm thick membrane of silicon nitride. The parallel flow channel (b) was chosen to have an area to length ratio 3.4 times that of the main channel.The restoring force is provided by a 12μ thick mylar diaphragm with 150nm of sputtered Nb on each side, whose displacement is read by a planar superconducting coil (c) with the help of a D.C.SQUID (10-11). Displacement calibration comes from the capacitor formed by one side of the diaphragm and a copper plate (d) placed about 100μ from it. In the absence of liquid in the cell, the detector can resolve 1.7×10^{-13}m(Hz)$^{-1/2}$ for a current of 300 mA in the planar coil. With superfluid He^4 in the cell at temperatures where ρ_s/ρ is essentially 1.0, the resonator is seen to oscillate at 6.225 Hz .This frequency is within 5% of 5.98 Hz calculated from the measured spring constant of the diaphragm and nominal dimensions of the flow channels.

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The experimental cell is connected to the bottom of a single-shot charcoal-pumped He^3 fridge which, in the absence of the cell, can run for several days at T=225 mK (12). A needle valve on the fill line is used to isolate the cell from fill-line perturbations.The fridge is held rigidly at the top and bottom with respect to the dewar. During each run, the entire dewar is suspended from a vibration isolation stage consisting of a 1000 kg platform resting on soft air-springs. The laboratory is located at bedrock level in the lower basement of a building. An enclosure with sound-proofing foam is placed around the dewar to reduce acoustical input into the experiment. There is no liquid nitrogen in the dewar and the ^{4}He bath is pumped down to 1 torr and slowly warms toward 4K during the data collection. We believe that the ^{3}He in the fridge is not boiling owing to its low vapour pressure at 0.3 K. Thus every effort is made to eliminate external sources of vibration. The actual data are taken in the middle of the night when the disturbances in the building are minimal.

3. OPERATION

In a given run a small constant drive is applied at the resonant frequency and the peak displacement for each half cycle is measured and stored in a computer. Fig. 2 shows a typical time development of the oscillation amplitude. The amplitude grows toward some steady-state value but this growth is interrupted by dissipative phase-slip events that produce abrupt decreases in the amplitude.On the actual waveform of the diaphragm displacement vs. time, a phase-slip is registered as a sudden change in the velocity (i.e. the slope), taking place in a time less than 10^{-3} second, which is the time constant of a low pass filter in the electronics recording the waveform.

It is clear from data similar to that in figure 2 that with this particular apparatus the phase slips occur at random times and have varying sizes. From the waveform of actual diaphragm displacement one observes that the phase slips do not always occur at the instantaneous maximum of the velocity. Both these observations suggest that the dynamical processes causing these events are not intrinsic to the liquid. Rather, the slips may be triggered, perhaps well below the intrinsic critical velocity in the small channel, by some external mechanical disturbance.

A spectrum of the diaphragm's displacement indicates that the Helmholtz resonance is randomly driven at amplitudes of about 0.01 nm. The scatter in the data of figure 2 is about 0.004 nm. These values can be compared to the typical amplitude where phase slips begin to occur (0.8 nm) and the actual size of the smallest slips which appear (0.023 to 0.026 nm). It is interesting to note that these smallest slips are within 10% of the estimated size for 2π phase-slips.

Based on these preliminary observations we plan to change the size and shape of the small channel and improve the vibration isolation. We hope these changes will shed light on the mechanisms that give rise to reproducible 2π phase-slips.

Figure 2. Phase-slips in the plot of amplitude vs. time for a constant drive. Each dot represents a half-cycle. The smallest jumps are close to 0.024 nm, the expected size for a 2π slip.

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