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Physica B 284–288 (2000) 81–82

PHYSICA B

www.elsevier.com/locate/physb

An aperture array oscillator in superfluid ^{4}He

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Abstract

We present studies of superfluid ^{4}He flow through an array of apertures using a diaphragm-aperture oscillator technique. The apertures, which have diameters of the order of 100 nm and are typically spaced a few microns apart, are made in a 90 nm thick SiN membrane. We have measured the supercritical flow through the array as a function of temperature and oscillator drive. At low temperatures, the critical velocity decreases linearly with increasing temperature. At moderately higher drive levels, the supercritical flow becomes progressively more noisy due to the increasing number of phase slips induced from one half-cycle to the next. Finally, at drive levels of the order of 1000 times higher than the critical drive, large collapses occur which significantly reduce the oscillator's amplitude.

Keywords: Aperture array; ^{4}He superfluid; Josephson effect; Supercritical flow

1. Introduction

The strong analogy that exists between superfluids and superconductors has motivated the search for Josephson effects in ^{3}He and ^{4}He. Studies of supercritical ^{4}He flow through single small apertures (with or without a larger parallel path) have provided many insights into the nature of vortex nucleation and quantized phase slippage [1]. Still, an *ideal* Josephson junction (with a sinusoidal current-phase relation) has not been observed in ^{4}He. The most promising possibilities rely on experiments performed near T_λ, where the coherence length diverges. Although the supercurrent is small near T_λ, it could be amplified by an array of apertures (acting coherently). Indeed recently, in ^{3}He, an array of small apertures has been found to behave as a single weak link and to demonstrate the predicted Josephson effects [2]. Encouraged by these results, we have begun to study the behavior of an aperture array in ^{4}He. This work deals with the temperature range ($0.28\ \text{K} < T < 2\ \text{K}$) where the current-phase relationship is linear.

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2. Experiment

Our experimental technique, developed by Zimmermann [3], and Avenel and Varoquaux [4], utilizes a diaphragm-aperture superfluid oscillator. In this work, the aperture array consists of 1280 holes ($0.2\ \mu\text{m} \times 0.1\ \mu\text{m}$) arranged in a 32×40 grid spaced 1 μm apart in a 90 nm thick SiN membrane. The low-temperature resonance frequency is 326 Hz. The current through the apertures is measured while slowly ramping the drive (pressure), on resonance. The response curves are recorded with a lock-in amplifier.

3. Results and discussion

Fig. 1 shows a typical response curve for this aperture array. The second kink in the slope is only found in multiple aperture devices, and indicates the presence of a bias, or trapped circulation. This circulation is slowly removed by single phase slips (or low multiples) as the drive is increased. The initial bias is hysteretic in that it depends on the manner in which the oscillator has been excited in previous sweeps. In general, low drive levels tend to keep the oscillator in a constant (near zero) bias state.

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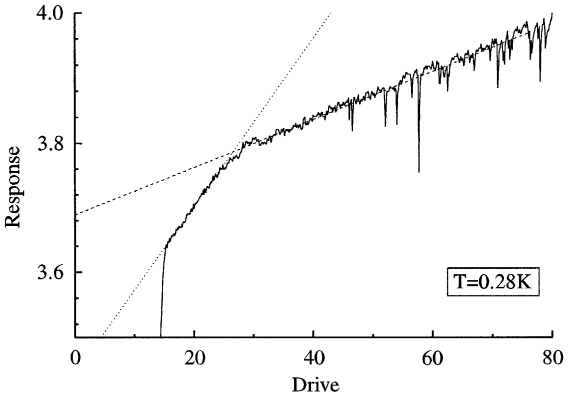

Fig. 1. The two distinct slopes in the supercritical regime indicate that trapped circulation among the apertures is slowly unwound as the drive is increased. The units are arbitrary, but consistent with Fig. 2.

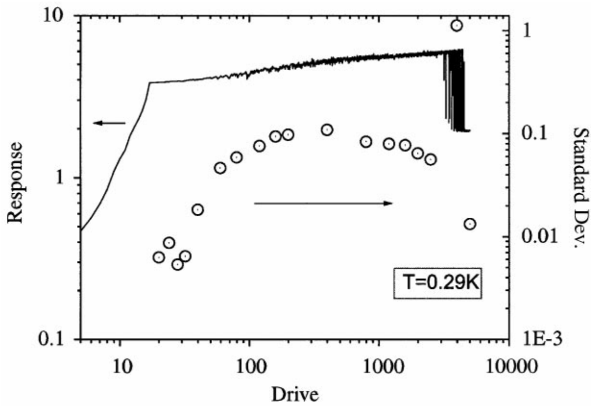

Fig. 2. This response curve shows the progressive increase in the number of phase slips (per half-cycle) as the drive is ramped up. The sudden onset of collapse events occurs at ~ 1000 times the critical drive.

In addition, we find that the temperature dependence of the critical velocity (with near zero bias) is consistent with the thermal activation model for vortex nucleation typically seen in single holes [1]. In this case, for $(0.28\ \mathrm{K} < T < 1.0\ \mathrm{K})$,

$$V_c(T) = V_{c0}\left(1 - \frac{T}{T_0}\right),$$

where V_{c0} is 1.89 m/s and T_0 is 2.59 K.

At moderate drive levels, progressively larger drops in amplitude indicate high multiples of phase slips. An analysis of the increasing "scatter" (Fig. 2) with drive indicates that the number of slips reaches between 200–300 per half cycle at drive levels close to 50 times the critical drive (when phase slips first set in). Finally, at drive levels ~ 1000 times higher than the critical drive, there is a sudden onset of giant phase shifting collapses in the oscillator's amplitude. The strong dissipation effectively "plugs" the apertures and thereby lowers the oscillator's resonance frequency.

Future work may help shed light on the feasibility of using an aperture array for Josephson effect experiments near the lambda point.

Acknowledgements

This work is supported by NSF and NASA.

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