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Pinned Vortex Density in He-4 Films Produced and Detected by Third Sound Resonances

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Resonant frequencies in a circular third sound resonator are shifted by DC persistent current flow fields present in the resonator. Each mode is shifted differently according its "overlap" with the flow. Measurements of these shifts consequently reflect the flow field, and hence the distribution of vortices. In addition, large amplitude circularly polarized third sound modes are used to create and destroy the flow states. Several conclusions can be drawn from the experiments: 1) Vortex densities of hundreds of thousands per square centimeter exist in quasi-equilibrium; 2) Vortex distributions include large densities of both circulation senses polarized to different radii within the cell; 3) Pinning strengths are consistent with the bulk pinning model of Schwarz[1] applied to a film; and 4) Third sound amplitudes with AC flows approaching the Feynman critical velocity create new vorticity. These results offer validity to the hypothesis that pinned vortices are a pervasive feature of superfluid films at low temperatures.

1. Introduction

Third sound Doppler shifts have been used in the past as a probe of persistent currents in both time of flight[2] and resonance[3] configurations. In a circular resonator, the shift takes the form of a splitting of the degenerate modes corresponding to left and right rotating travelling waves. Each mode is affected differently according to the overlap of the persistent flow field with the wave flow field. The size of these shifts can be calculated by numerically solving equations of motion which include an annular flow field $v_0(r)$.

The exact form of $v_0(r)$ could be determined by a measurement of all of the modes. Measurements of just a few modes results in an incomplete or "filtered" knowledge of its functional form but none the less reflect its general behavior. Thus, the mode splittings not only indicate the magnitude of the circulation in the cell but also the general form of the persistent flow field. Any significant deviation from $v_0 \sim 1/r$ will provide a quantitative estimate of the pinned vortex density present in the film.

Turning now to the generation of the persistent flows, we have observed that this can be accomplished simply by driving one of the rotating third sound modes at an amplitude such that the wave's peak flow field is near the expected critical velocity in the film. In effect, we have used the third sound wave to "swirl" the film up or back down. The classical swirling process is a result of nonlinear transfer of momentum from the wave field to the fluid particles. In the superfluid, it must involve the separation, and subsequent permanent polarization or migration of vortex pairs. Only pairs which recombine after traversing the cell result in a net circulation change. Vortices which remained pinned only contribute to deviations from macroscopic curl free flow.

2. Experimental

The third sound resonator consists of a circular cavity formed in an 8μm gap between two microscope slides. Stycast 1266 epoxy holds the plates together and defines the outer perimeter at a=6.15mm. A gold film evaporated on the inner surfaces provides electrostatic drive plates at two different angular orientations and a capacitive pickup transducer. Both the drive forces and the pickup sensitivity are well characterized so that capacitance oscillations of the pickup plate can be translated into wave height and velocity fields appropriate for each mode. A .13mm radius central hole provides both access to the interior of the resonator, and a topology favorable to circulation.

The film is swirled by applying up to 30V to the drive plates with a 45° phase shift. The drive forces are frequency doubled and the resulting 90° phase

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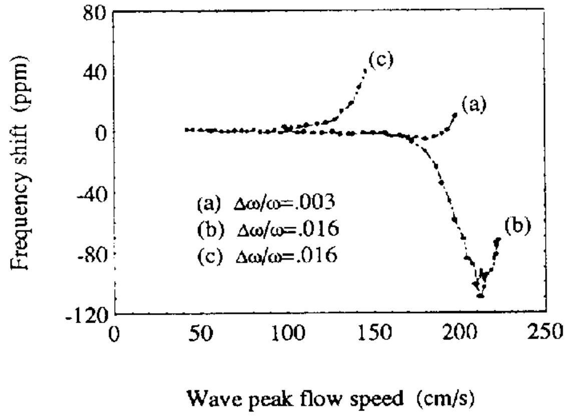

Figure 1. Response to wave amplitude. Frequency shifts are deviations from the values shown.

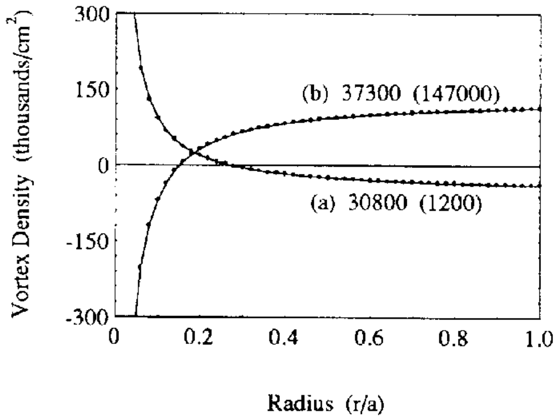

Figure 2. Approximate vortex densities. The numbers shown are the circulation quanta in the hole and the (circulation quanta in the whole cell).

shift couples directly to the rotating travelling waves states. The mode is resonated at a high amplitude for a period of time and the splittings are subsequently checked by observing the free decay frequencies of several modes after excitation to a small amplitude. The circulation polarization can be determined by interchanging the drives and observing the relative strengths of the left and right polarized drive response.

3. Discussion

All data presented is at .12K and a film thickness of 3.2nm where the Feynman critical velocity $h/2m_4d$ is 248cm/s. Figure 1 exhibits the critical nature of the swirling process in three situations: a) driving up a small circulation; b) driving up a large circulation; and c) driving down a large circulation. Low and high circulations (a,b) are seen to require a large amplitude to change when driven up although the latter looses circulation at first. When the high circulation is driven down (c) a much smaller amplitude is necessary. Here, the change in frequency is still up since the shifted down mode is being changed back toward degeneracy. Curves (b) and (c) show that vortex de-pinning occurs more readily in the presence of high flows. Extensive modeling of pinning shows these flows to be consistent with the gold surface roughness as measured by an STM.

Figure 2 shows the derived vortex densities for circulations prepared to emphasize vortex pinning characteristics. Here, for curve (a) the m=1 mode was driven to swirl the film up, and the m=2 mode was driven to swirl the film down. This process results in a large net positive vorticity in combination with a polarization of opposite vorticity toward the outer regions of the resonator. Curve (b) was prepared the other way around and results in a more uniform distribution. No evidence of relaxation of these distributions with time has been observed.

Both the critical amplitude effects and the hysteretic response of the modes to swirling up and down clearly show the presence of large densities of pinned vortices. The vortex distributions result in persistent currents with macroscopic shear flow and permanent polarization of vortices of opposite circulation. The critical amplitudes are consistent with a simple model of vortex pinning to the typical roughness of the gold substrate.

(1) K. W. Schwarz, Phys. Rev. Lett., 69, 3342 (1992)

(2) K. Telschow, I Rudnik, and T. Wang, Phys. Rev. Lett., 32, 1292 (1974)

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