Film thinning in unsaturated superfluid ^{4}He films during persistent flow

D. T. Ekholm
Department of Physics and Astronomy, University of Massachusetts, Amherst, Massachusetts 01003

R. B. Hallock
*Laboratory for Atomic and Solid-State Physics, Cornell University, Ithaca, New York 14853
and Department of Physics and Astronomy*, University of Massachusetts,
Amherst, Massachusetts 01003*
(Received 9 August 1978)

We report measurements of the thickness of unsaturated superfluid ^{4}He films in persistent flow as a function of persistent current velocity. Our results are in quantitative agreement with the predictions of Kontorovich, and thus disagree with the conclusion of Rudnick and coworkers that ρ_s/ρ has an enhanced velocity dependence in these films.

Kontorovich[1] and Tilly[2] predicted that a moving superfluid ^{4}He film would be thinner than a static film. Keller[3] was the first to test this prediction to high accuracy, and found the surprising result that in relatively thick saturated films, the thickness was unchanged as a function of velocity to within ± 5 Å. Numerous experiments[4] followed that of Keller and for the most part there is now general agreement that in these saturated films the film does thin with velocity as predicted. No explanation for Keller's original experiment has been advanced.

Although there is no *a priori* reason to suspect that for much thinner unsaturated ^{4}He films the situation should be different, there has been much less experimental work in this area. Until the present work the only experiment to test film thinning in unsaturated films was that of Telschow[5] *et al.* In that work third-sound techniques were used to measure the thinning of the film, where the film flow velocity was induced by means of a heater. Care was taken to ensure that the flow velocity of the film was subcritical. The results of this work indicated that either the film was not thinned as a function of velocity (in agreement with the work of Keller on thicker films) *or* that what was observed was a simultaneous thinning of the film as predicted, and an unexpectedly large dependence on velocity of the effective value of the superfluid density in the film. The present results on film thinning as a function of the velocity of the film in *persistent* flow, are in agreement with the predictions of Kontorovich as applied to our apparatus. This shows that there is no unexpectedly large velocity dependence of the superfluid density in films of this type.

The experimental apparatus (see Fig. 1) is an adaptation of that first used by Telschow and Hallock[6] to study the stability of persistent film currents. Application of an amount of heat $\dot{Q}$ to heater Q results in a flow of helium at velocity v_3 along branch No. 3 given by $\dot{Q} = \langle \rho_s \rangle v_3 \, dP_3 (L + TS)$, where $\langle \rho_s \rangle$ is the reduced superfluid density in the film of thickness d, P_3 is the perimeter of the glass surface, L is the latent heat, T the temperature, and S the entropy. For low values of $\dot{Q}$ the circulation around the loop $K = \int v \, dl = v_2 l_2 - v_1 l_1$ remains zero. Above a critical value of $\dot{Q}$, the velocity v_1 reaches the critical velocity. A further increase of $\dot{Q}$ results in an increase of v_2, while v_1 remains essentially constant. Thus, the circulation around the loop can be made to be nonzero. Subsequent reduction of the heat applied, $\dot{Q}$, to zero results in a finite circulation. For films in the appropriate range of thickness and temperature, the final circulation is stable and a per-

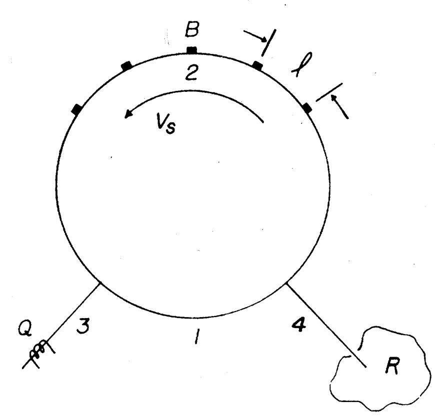

FIG. 1. Schematic of the persistent current film flow path. The Pyrex annual ring has a diameter of approximately 10 cm. The reservoir R consists of 8 g of Al_2O_3 powder (0.05 μm) and provides a large surface area to stabilize the film thickness.

sistent film current exists on the ring. The persistent current velocity can therefore be selected by the use of an appropriate value for $\dot{Q}$.

The velocity of the persistent current, as well as the film thickness, is determined using the techniques of Doppler-shifted third sound.[7] Third-sound generators and detectors are fabricated by evaporating Al strips of approximate dimensions 1 cm × 0.25 mm × 50 nm, onto the Pyrex film-flow substrate with a separation $l = 1$ cm. When in operation a generator strip, typically B in Fig. 1, is driven with a single-cycle-sine voltage pulse of frequency 1.6 kHz at a repetition rate of 30–100 Hz. We have observed that such pulses do not enhance the natural decay of persistent currents in thinner films at temperatures similar to those studied here.

The entire apparatus was mounted in a brass chamber which could be sealed by means of a superfluid valve and was mounted at the end of a standard cryostat. Temperature control was attained by stabilization of the vapor pressure above the pumped dewar by means of a manostat.

The velocity of third sound is related to the character of the film through[8]

$$C_3^2 = (\langle \rho_s \rangle / \rho) f d (1 + TS/L)^2 \ .$$

For thin films of the type studied here, it is appropriate to take $f = n\alpha d^{-(n+1)}$, where n is a constant and α is the Van der Waals constant. Thus, we have

$$C_3^2 = n(\langle \rho_s \rangle / \rho)(\alpha / d^n)(1 + TS/L)^2 \ . \tag{1}$$

If we adopt the notation that d_0 is the thickness of the static film, the Kontorovich prediction can be written under isothermal conditions, and in the absence of mechanical pressure differences and dissipative terms can be written

$$\frac{\langle \rho_s \rangle}{\rho} \frac{v_s^2}{2} - \frac{\alpha}{d^n} = -\frac{\alpha}{d_0^n} \ , \tag{2}$$

where v_s is the constant velocity of the superfluid film. We thus find

$$\tfrac{1}{2} n (1 + TS/L)^2 [(\langle \rho_s \rangle / \rho) v_s]^2 = C_3^2 - C_{30}^2 \ , \tag{3}$$

where C_{30} is the third-sound velocity on the static film.

In the presence of a film flow of velocity v_s third sound is Doppler-shifted according to the expression $C_{\pm} = C_3 \pm \langle \rho_s \rangle v_s / \rho$. With reference to Fig. 1, if the downstream and upstream third-sound-pulse arrival times are t_2 and t_1, respectively, we can write

$$\tfrac{1}{2} \Delta C \equiv \tfrac{1}{2}(C_+ - C_-) = \tfrac{1}{2}(t_2^{-1} - t_1^{-1}) l = \langle \rho_s \rangle v_s / \rho$$

and

$$C_3 = \tfrac{1}{2}(C_+ + C_-) = \tfrac{1}{2}(t_2^{-1} + t_1^{-1}) l \ .$$

Thus, in terms of measurable quantities we would expect to find

$$\tfrac{1}{2} n (1 + TS/L)^2 \tfrac{1}{2} (\Delta C)^2 = C_3^2 - C_{30}^2 \ . \tag{4}$$

The quantity n is determined experimentally from measurements of the third-sound velocity C_{30}, the static thickness d_0, and the use of Eq. (1). The thickness d_0 is determined in the usual way through the use of $d_0^n = 27[T \ln(P_0/P)]^{-1}$, where P_0 is the saturated vapor pressure at temperature T and P is the pressure in the experimental chamber, which is in equilibrium with a film of thickness d_0. We find[9,10] $\tfrac{1}{2} n = 1.39 \pm 0.17$ independent of temperature, and d_0 over the range studied.

In practice, the quantities C_+, C_-, and then C_{30} are measured alternately, repeatedly. This is done to avoid the effects of small drifts in the film thickness which could seriously affect the value of $C_3^2 - C_{30}^2$, since this difference is the difference between two large numbers.

A typical example of an experimental test of Eq. (4) is shown in Fig. 2. The slope predicted is shown as a solid line on the figure. The agreement between the predictions of Kontorovich and the measurement is excellent. Typically, four such measurements were

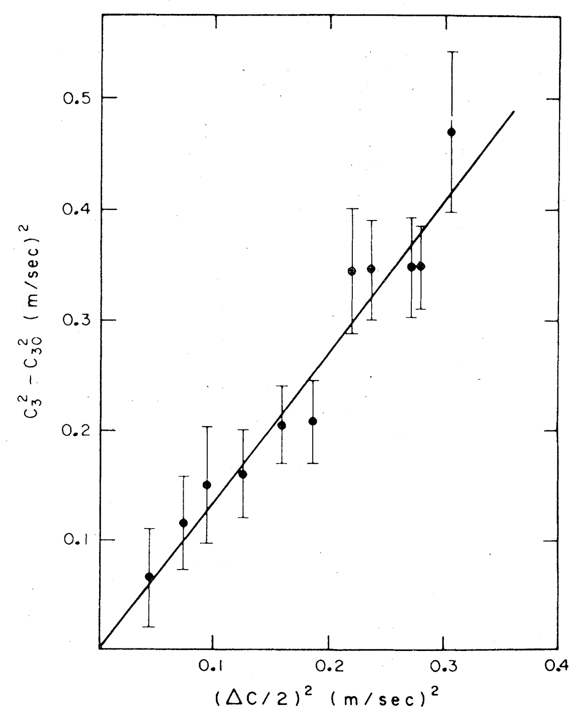

FIG. 2. Typical example of the observed $C_3^2 - C_{30}^2$ plotted against the observed $(\tfrac{1}{2}\Delta C)^2$. The solid line is a least-squares fit to the data in this particular case (slope: 1.36 ± 0.05). Here we have $T = 1.27$ K and $d = 9.4$.

TABLE I. Summary of experimental conditions and results of these measurements. The observed slopes β are in good agreement with the expected result $\frac{1}{2}n = 1.39 \pm 0.17$. The quantity $(1+TS/L)^2$ is a correction of less than 1% and has been neglected here. We find $\bar{\beta} = 1.40 \pm 0.04$.

T	d_0	β
1.27	9.4	1.36 ± 0.05
1.27	11.6	1.39 ± 0.09
1.27	14.7	1.48 ± 0.06
1.40	9.3	1.39 ± 0.05
1.40	11.5	1.37 ± 0.03
1.40	14.3	1.43 ± 0.03

made for each temperature and thickness studied. The averaged slopes β from these measurements are presented in Table I.

We conclude that in the case of films of the sort we have studied under conditions of persistent flow, the film thins in good agreement with the predictions of Kontorovich. This agreement indicates that $\langle \rho_s \rangle / \rho$ in unsaturated helium films does not have an unexpectedly large dependence on the velocity of the film under nondissipative persistent flow conditions.[11]

ACKNOWLEDGMENTS

One of us (R. B. H.) appreciates the hospitality of the Aspen Center for Physics during the period in which this manuscript was written. We appreciate beneficial conversations with J. D. Reppy and I. Rudnick. This work was supported by the NSF by Grant Nos. DMR 76-08260 and DMR 78-07762.

---

*Permanent address: Dept. of Physics and Astronomy, University of Massachusetts, Amherst, MA 01003.

[1] V. M. Kontorovich, Zh. Eksp. Teor. Fiz. 30, 805 (1956) [Sov. Phys. JETP 3, 770 (1956)].

[2] J. Tilley, Proc. Phys. Soc. London 84, 77 (1964).

[3] W. E. Keller, Phys. Rev. Lett. 24, 569 (1970).

[4] See, for example, E. van Spronsen, H. J. Verbeek, R. de Bruyn Ouboter, K. W. Taconis, and H. van Beelan, Phys. Lett. A 45, 49 (1973); G. A. Williams and R. Packard, Phys. Rev. Lett. 32, 587 (1974); E. B. Flint and R. B. Hallock, Phys. Rev. B 11, 2062 (1975); R. B. Hallock in *Quantum Statistics and the Many Body Problem,* edited by S. B. Trickey *et al.* (Plenum, New York, 1975), p. 185; G. M. Graham and E. Vittoratos, Phys. Rev. Lett. 33, 1136 (1974)); R. K. Galkiewicz, K. L. Telschow, and R. B. Hallock, J. Low Temp. Phys. 26, 147 (1977); G. M. Graham, J. Low Temp. Phys. 27, 177 (1977). D. S. W. Kwoh and D. L. Goodstein, J. Low Temp. Phys. 27, 187 (1977).

[5] K. Telschow, I. Rudnick, and T. G. Wang, J. Low Temp. Phys. 18, 43 (1975).

[6] K. L. Telschow and R. B. Hallock, Phys. Rev. Lett. 37, 1484 (1976).

[7] See, for example, K. R. Atkins and I. Rudnick, in *Progress in Low Temperature Physics,* edited by C. J. Oorter (North-Holland, Amsterdam, 1970), Vol. 6, Chap. 2.

[8] D. Bergman, Phys. Rev. 188, 370 (1969); Phys. Rev. A 3, 2058 (1971); see also R. K. Galkiewicz, K. L. Telschow, and R. B. Hallock, J. Low Temp. Phys. 26, 147 (1977).

[9] These measurements are not carried out at the same time as the Doppler-shift measurements, since the line connecting the pressure gauge to the experimental chamber causes gradual drifts in the film thickness if it is left open.

[10] For films in this thickness range one would expect $n=3$. [See, for example, E. S. Sabisky and C. H. Anderson, Phys. Rev. A 7, 790 (1974)].

[11] In actual practice all persistent currents are thought to be metastable. For the films studied here, the fractional decay of v_s per decade of time ranged from a high of 4% ($d_0 = 9.3$, $T = 1.4$ K) to an unobservably small value for thicker films at lower temperatures.