be injected into a plasma from large limiter plates with good secondary electron yields to keep the sheath potential low.

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# Behavior of Persistent Currents under Conditions of Strong Decay

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We report observations of the decay of persistent currents of thin superfluid $^4$He films for which the superfluid velocity deviates strongly from the previously observed $\log t$ behavior. We present data which document the evolution of this behavior as a function of film thickness. The Iordanskii-Langer-Fisher theory does not accurately describe our observations.

Superfluid $^4$He has the remarkable ability to attain a state of macroscopic persistent flow. It is generally assumed that such flow is, in fact, only metastable. In some cases the instability is weak enough to render the flow persistent over laboratory lifetimes. In other cases the metastability becomes clearly apparent. Previous to this report[1] all studies of the degradation in time of these persistent currents yielded results which could be adequately described by

$$v(t) = a - b \log t, \tag{1}$$

where $v(t)$ is the macroscopic velocity of the flow at time $t$ and $a$ and $b$ are empirical parameters. In particular, Kojima *et al.*,[2] Kukich, Henkel, and Reppy,[3] and Langer and Reppy[4] have observed that the flow of bulk $^4$He in restricted geometries (compressed powders, Vycor, etc.) obeys Eq. (1). The Iordanskii-Langer-Fisher[5,6] (ILF) model of persistent-current decay generally predicts Eq. (1) under conditions for which the superfluid velocity makes small deviations from a critical velocity, $v_c$.

Telschow and Hallock[7] have also reported general agreement with Eq. (1) in studies of persistent flow in thin $^4$He films, but they observed this behavior to be obeyed even for changes in the velocity of as much as 60% away from the initial[8] velocity, $v_0$. We present results here of studies of persistent currents in $^4$He films for which the decays in some cases appear to cause the complete extinction of the flow. Our results as a function of film thickness show clearly for the first time the evolution of deviations from Eq. (1).

The apparatus used for the present work is an improved version of that used[7,9] earlier in this laboratory. Persistent currents are generated on a Pyrex annular ring without rotation using a thermal technique.[7] The speed of the persistent flow is measured using the well-known techniques of Doppler-shifted third sound.[10] We have observed that the strength and nature of the velocity decays does not depend on the presence of the third sound necessary to make the measurements. Film thickness values are determined[11] from the temperature and vapor pressure and are consistent to within a few percent with thickness values deduced[11] from the observed third-sound velocity. Changes in the film thickness due to the flow of the film are observable[12] but are too small to be relevant here.

Data on the decay of the persistent currents are obtained from measurements of the flow velocity as a function of time. In each of the cases presented in Fig. 1 we have plotted $v/v_0$ to facilitate the comparison although $v_0$ was within 20% of 25 cm/sec for each case. It is observed that even for substantial changes in the film velocity the persistent-current decays are remarkably well represented by Eq. (1). Our present results are in qualitative agreement[13] with earlier work[7] in the limited region of overlap of the data. A clear evolution of deviations from Eq. (1) is observed as the film thickness is reduced below about eight layers.

It is clear that one must search beyond Eq. (1) to describe our observations. A simple empirical expression fits the data rather well over the full range of film thickness values studies. We find

$$v(t) = A(1+Bt)^{-n}. \qquad (2)$$

This is consistent with a deceleration of the form

$$dv/dt = -cv^{\alpha}, \qquad (3)$$

where $\alpha = n^{-1}+1$. The observed dependence of $\alpha$ on film thickness is shown in Fig. 2.

The form Eq. (3) can be recovered from the ILF theory if the full expression for the activation energy, $E_a$, of a vortex pair oriented perpendicular to the substrate is used, i.e.,

$$E_a = (d\langle\rho_s\rangle K^2/2\pi)\{\ln(K/2\pi va) - 1\}.$$

Here $K$ is the quantum of circulation and $a$ is the vortex core radius. With this $\alpha = d\langle\rho_s\rangle K^2/2\pi k_BT$ and this[14] is shown on Fig. 2 as the solid curve. We conclude that the ILF theory is only in qualitative agreement with the data. The observed dependence of $\alpha$ on $d$ is more closely represented by the form $\alpha = \alpha_0 + (d-d^*)^4$ over the relatively limited range of film thickness values for which persistent-current decays can be accurately measured. We find $\alpha_0 \simeq 2$. For a true two-dimensional superfluid we would expect[15,16] Eq. (3) with $\alpha \simeq 3$.

An objection to the use of the ILF theory[5,6] has been advanced by Donnelly and Roberts.[17] They have argued that the velocities needed to provide an appropriate energy barrier are much larger than the macroscopic currents[18] typically present in a restricted-geometry flow apparatus. Donnelly and Roberts propose that a finite barrier exists even in the absence of superflow due to the presence of boundaries in the real system. The competition between the barriers for forward and backward nucleation yields a prediction

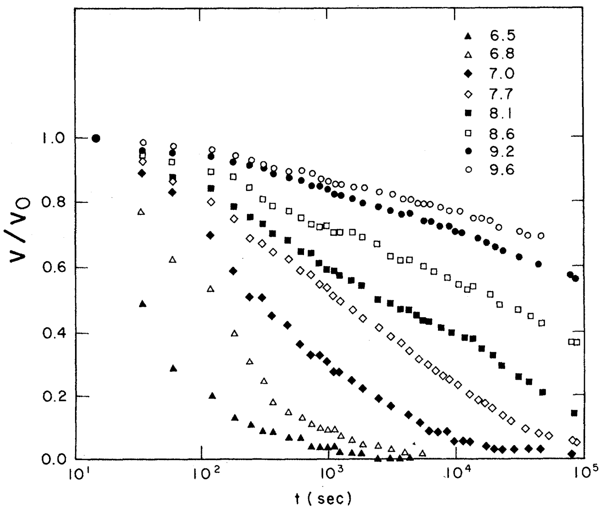

FIG. 1. Velocity of the metastable film currents as a function of time, at $T = 1.45$ K. The ratio $v/v_0$ has been used to facilitate comparison among the various film thickness values. The numbers in the upper right are the measured film thickness values in atomic layers.

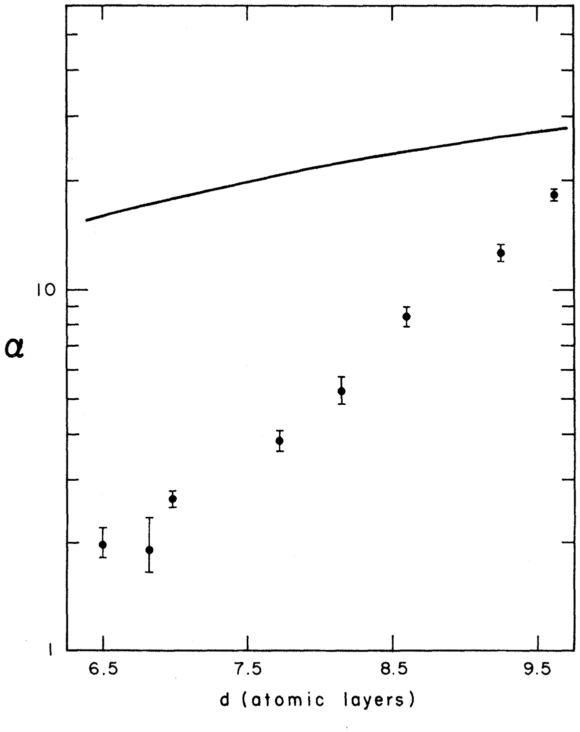

FIG. 2. The exponent $\alpha$ as a function of film thickness. The solid curve is the value of $\alpha = d\langle\rho_s\rangle K^2/2\pi k_BT$ at $T = 1.45$ K.

for the decay of persistent flow of the form given by Donnelly, Hills, and Roberts[19] as

$$v = F \ln\left(\frac{1 + G\exp(-\nu_0 t)}{1 - G\exp(-\nu_0 t)}\right). \tag{4}$$

Here $F = k_B T/p_c$, where $k_B$ is the Boltzman constant, $T$ the temperature, and $p_c$ the momentum of the critical excitation. $G$ is a number which depends on the initial velocity of the persistent flow and

$$\nu_0 = (2nKfp_c/k_B T)\exp(-\Delta E/k_B T),$$

where $n$ is the linear density of candidates for nucleation, $f$ is an attempt frequency, and $\Delta E$ the barrier height for $v = 0$. In general Eq. (4) represents the data reasonably well although for times late in the evolution of the persistent flow the data indicate that the velocity decreases more slowly than predicted.[19] The quantity $\nu_0$ as deduced from fits to the data of Fig. 1 is shown in Fig. 3 versus the thickness of the helium film. The solid lines are the predictions[19] for two arbitrary values of $f$.

We have also observed that it is possible to change the rate of decay of a given metastable flow merely by changing the temperature. An example of this is shown in Fig. 4. The solid curve represents the time evolution of the velocity of a film at $T = 1.50$ K at a thickness of eight atomic layers. During a subsequent decay from the same initial velocity, represented by the solid circles, the temperature was changed for a time to a lower value of 1.40 K. Upon returning the temperature to its original value the decay rate increased. The crosses plotted here represent the coordinates $(v, t - t_0^*)$ where $t$ is the clock time and $t_0^*$ is the interval of time during which the film was at the lower temperature. One interpretation, among others, of this observation is that the vorticity present in the film is frozen in by a lowering of the temperature. Under this point of view what matters is the thermally activated *motion* (hopping) of the vortices rather than the thermal nucleation of the vortices themselves.

In conclusion, our observations of the complete decay of metastable superfluid $^4$He film currents has revealed substantial deviations from the decay rule encountered in all previous experiments. Predictions based on the ILF theory[5,6] are in qualitative but not quantitative agreement with our results and hence we conclude that that theory is incomplete. The predictions of Donnelly,

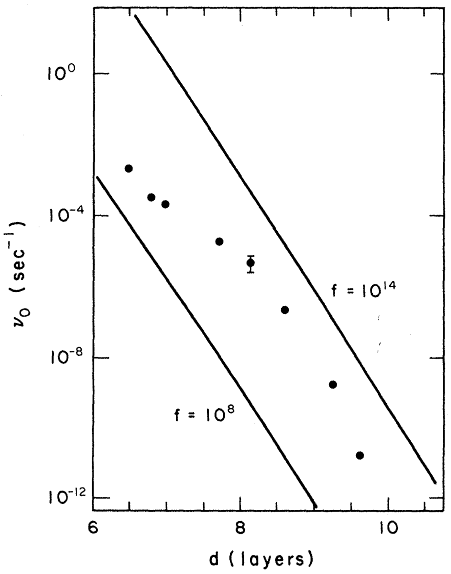

FIG. 3. Nucleation rate $\nu_0$ as a function of film thickness at 1.45 K. The circles represent the observed values of $\nu_0$ and the solid lines are obtained from Ref. 19.

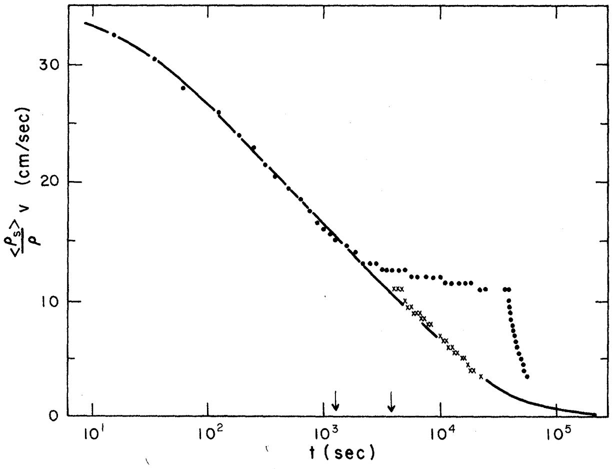

FIG. 4. Decay of a metastable current subject to a change in the temperature. The solid curve shows the decay at the constant temperature of 1.50 K. The symbols display the observed decay as discussed in the text. The transition to lower temperatures was made during the interval between the arrows. The later warmup interval is compressed by the time scale. When the persistent current is warmed it continues its decay—it does not reproduce a virgin decay with a lower initial velocity. $t_0^*$ was defined as the interval of time between the midpoints of the cooldown and warmup periods. At large values of the time several of the data represented by the dots were essentially superimposed; this results in the appearance of more x's than dots for these data.

Hills, and Roberts[19] are in qualitative agreement with the data except perhaps at times late in the evolution of the current decays. A quantitative test awaits theoretical estimates for the parameters which are inherent in the theory.

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

[11] We have used $d^3 = 27[T\ln(P_0/P)]^{-1}$, where $d$ is the film thickness in atomic layers, $P_0$ the saturated vapor pressure at temperature $T$, and $P$ the pressure in the container which houses the persistent-current flow path. These measurements are consistent to within a few percent with thickness values deduced from $C_3^2 = 3\langle\rho_s/\rho\rangle(\beta/d^3)[1+TS/L]^2$, where $C_3$ is the third-sound velocity, $\langle\rho_s/\rho\rangle$ the reduced superfluid fraction in the film, $\beta$ the van der Waals constant, $S$ the entropy, and $L$ the latent heat.

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[13] One quantitative difference between this work and that reported in Ref. 7 is that a given decay here appears to occur in a somewhat thicker film than in the work reported in Ref. 7. A difference in the substrate could be the cause. The present work utilized a precision capacitive pressure gauge not available earlier and it is possible that our earlier thickness values were in error by a few tenths of an atomic layer. The relative comparisons presented here are of course unaffected.

[14] To calculate $\langle\rho_s\rangle$ we have used $\rho_s(1-D/d)$, where $\rho_s$ is the bulk superfluid density and $D = 0.5 + 2.45(\rho T/\rho_s T_\lambda)$.

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# Ultrasonic Attenuation near the 208-K Phase Transition of $RbAg_4I_5$

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Using general expressions for the velocity and ultrasonic attenuation coefficient we have analyzed ultrasonic data for the 208-K phase transition in $RbAg_4I_5$. From fitting the velocity in the high-temperature phase we obtain values for the strain and pseudospin coupling constants. We extract the intrinsic pseudospin relaxation rate from an analysis of the attenuation. The Jahn-Teller model is found to provide a good description of the ultrasonic behavior associated with the phase transition.

The 208-K phase transition in the superionic conductor $RbAg_4I_5$ has been of considerable interest recently.[1-13] The nature of this transition has been established to be three-dimensional Ising-like.[4] This conclusion is based on a study of the specific heat, which yields Ising-like exponents and amplitudes, and on a study of the birefringence in the ordered phase. The birefringence