The infrared stimulated emission is observed despite the absorption ($K \sim 40$ cm^{-1}) of the medium[15] due to background absorption and a strong neighboring absorption band at 1955 cm^{-1}, which has been identified[13] as a combination of the 985- and 970-cm^{-1} vibrations. The large absorption of the medium at 5 μ must first be saturated to allow the stimulated infrared radiation to propagate.

That the thermospectrum of the 8050-Å stimulated Raman line, which involves a shift of 1984 cm^{-1} from the laser frequency, and the thermospectrum of the stimulated-emission line at 5 μ peak at the same temperature indicate that both are due to phonons of 1984 cm^{-1}. Although we have observed optical-phonon-stimulated emission from benzene, such emission should be observable from many liquids, gases, and solids.

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DECAY OF SUPERFLUID "PERSISTENT CURRENTS"*

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Superfluid persistent currents are observed to decay with a logarithmic time dependence for flow velocities near the critical velocity. The temperature dependence of the decay rate and the critical velocity obtained from the experiment are discussed in terms of a thermal activation picture.

In recent persistent current experiments,[1] Clow and Reppy have observed a critical velocity proportional to the superfluid density near the transition. Langer and Fisher have proposed a critical-velocity mechanism[2,3] based on fluctuations of the superfluid order parameter. This mechanism leads to the observed temperature dependence for the critical velocity and, in addition, predicts a slow decay of the superfluid velocity with a logarithmic time dependence.

An analogous situation exists in superconductivity, where a thermally activated process, flux creep, leads to the logarithmic decay of persistent currents.[4-6]

The present experiment was undertaken to investigate the existence of the predicted decay process. The methods are similar to those described in Ref. 1; a detailed account of the experimental techniques will be published elsewhere. Persistent currents are formed in an annular container filled with a 500-Å pore filter material.[7] The currents are produced by rotating (~50 rad/sec) at a temperature above T_λ. The system is cooled while rotating to near 1°K. Then the rotation is slowly stopped. As the container is brought to rest, the superfluid slows until a "critical velocity" is reached. The angular momentum associated with the persistent current flow is then measured and a mean superfluid velocity deduced.

When the persistent-current flow velocities are near the critical velocity, the angular momentum of the persistent current decreases with time. The fractional change in angular momentum or superfluid velocity is shown in Fig. 1 as a function of time. The observation of the logarithmic time dependence for the decay of the persistent current provides strong support for the view that the superfluid flow is limited by thermal activation of a dissipative mechanism.

In addition to the determination of the decay rate at different temperatures, the experiment also provides data on the temperature dependence for superfluid density ρ_s and the critical velocity $v_{s,c}$. We shall discuss the relationship of these quantities in terms of a thermal-activation picture.

Following Langer and Fisher,[2,3] we assume that fluctuations provide the superfluid system access to states of smaller flow velocity and lower free energy. The decay rate is controlled by a free-energy barrier F_b, which must be overcome in the decay process. Then

$$dv_s/dt = Gf_0 \exp[-F_b/k_B T], \tag{1}$$

where G is a proportionality constant and f_0 is some molecular attempt frequency. The barrier function must be a decreasing function of v_s; so the decay process will become negligible at nonzero v_s. The critical velocity $v_{s,c}$ is obtained by setting the decay rate equal to a small number φ_0. Then

$$F_b(T, v_{s,c}) = \gamma kT, \tag{2}$$

where $\gamma = \ln(Gf_0/\varphi_0)$.

For sufficiently long times, the velocity will be changing slowly and F_b may be expanded in powers of $v_{s,c}-v_s$. Equation (1) will then have an approximate solution with a logarithmic time dependence. The fractional rate of logarithmic decay, R, is then given by

$$R \equiv \frac{1}{v_{s,c}} \frac{d(v_{s,c}-v_s)}{d\ln t} \cong \frac{1}{v_{s,c}} \frac{2.30kT}{\partial F_b/\partial v_s}. \tag{3}$$

In our discussion, we shall assume that the barrier is associated with a superfluid flow state (a vortex ring in the Langer-Fisher theory). Then, we expect that the temperature dependence of the barrier can be expressed as a factor, $\rho_s(T)$.[8] Thus,

$$F_b(T, v_s) = \rho_s(T) f(v_s). \tag{4}$$

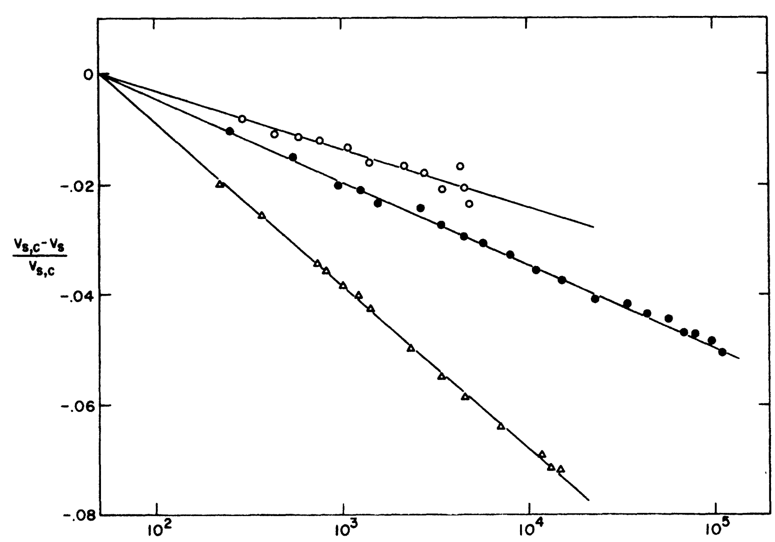

FIG. 1. The fractional change in superfluid velocity $(v_{s,c}-v_s)/v_{s,c}$ is shown as a function of time for three temperatures, $\Delta T = T_\lambda - T$, equal to 94 mdeg K (triangles), 135 mdeg K (closed circles), and 812 mdeg K (open circles).

By combining Eqs. (2) and (4) we have,

$$f(v_{s,c}) = \gamma k T/\rho_s. \quad (5)$$

The form of $f(v_s)$ is obtained by plotting, in Fig. 2, the measured quantity $\rho T/\rho_s = (\rho/\gamma k)f$ (solid circles) as a function of $v_{s,c}$. The strong v_s^{-1} dependence seen is in agreement with the vortex-ring model of Langer and Fisher.[2] Chester[9] has pointed out that a dimensional argument generally gives a v_s^{-1} dependence for the energy of a three-dimensional quantized flow.

The deviation from the v_s^{-1} form is also shown in Fig. 2, where the quantity $v_s\rho T/\rho_s$ is plotted as open circles.

The form of the barrier obtained from the data is

$$F_b = \gamma k(\rho_s/\rho)(Q/v_s)(1-v_s/v_0), \quad (6)$$

where $Q = 623$ cm sec^{-1}°K and $v_0 = 108$ cm sec^{-1}. The fractional rate of decay R is obtained by substituting the empirical barrier function, Eq. (6), in Eq. (3); then

$$R = \frac{R_\lambda}{1+(Q/v_0)(\rho_s/\rho T)}, \quad (7)$$

where $R_\lambda = -2.30/\gamma$ is the rate approached at the transition.

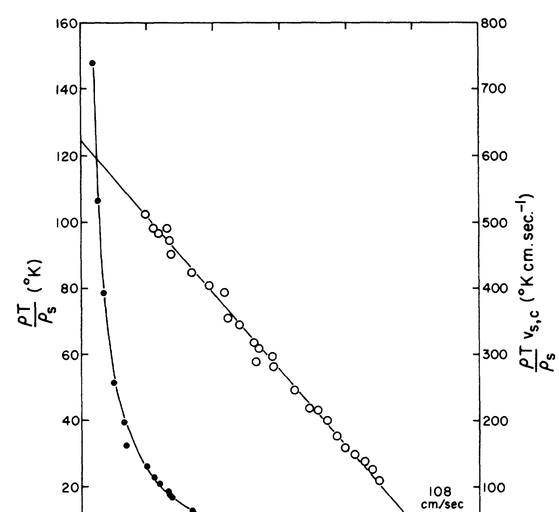

FIG. 2. The experimentally determined quantities $\rho T/\rho_s$ (solid circles) and $(\rho T/\rho_s)v_{s,c}$ (open circles) are shown as functions of the mean superfluid critical velocity, $v_{s,c}$. The solid curve through the $\rho T/\rho_s$ data (solid circles) is the function $\rho T/\rho_s = Q[v_{s,c}^{-1}-v_0^{-1}]$, where $Q=623$ cm sec^{-1}°K and $v_0=108$ cm sec^{-1}.

Figure 3 shows the measured values of the rate plotted against $T_\lambda - T$. The solid line is the value calculated from Eq. (7) when R_λ is taken as 5% per decade of time.

The agreement between the predicted and measured rates substantiates the assumption that the major part of the temperature dependence of F_b is contained in a ρ_s factor.

The success of the thermal-activation approach in relating the observations of the present experiment suggests that it might be fruitful to employ the same point of view in analyzing results from other critical-velocity experiments. Also, it is of interest to consider predictions based on other forms for the barrier function. One possibility is suggested by the flux-creep theory of Anderson.[5] A barrier function and predictions for the temperature dependence of the critical velocity and decay rate can be obtained by interpreting Anderson's theory in the context of liquid helium. In contrast to the observations of the present experiment, the fractional rate of logarithmic decay is found to blow up as the transition is approached. This unbounded increase would result in a depression of the onset temperature for superfluidity such as predicted and observed in the "one-dimensional" superconducting case.[10,11]

The preliminary results of the present experiment have been reported elsewhere.[12] The authors wish to acknowledge many helpful discus-

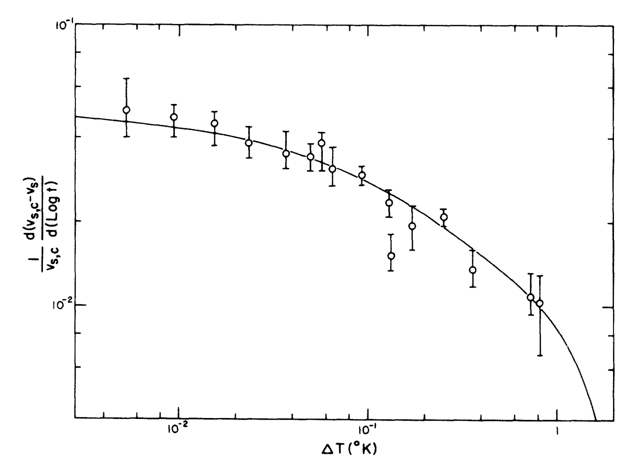

FIG. 3. The decay rate, $R = v_{s,c}^{-1} d(v_{s,c}-v_s)/d\ln t$ is shown as a function of $\Delta T = T_\lambda - T$, where T_λ is taken as the onset temperature for superfluidity in 500-Å filter material. A 1.5 ± 0.3 mdeg K depression of the onset temperature below the bulk value is observed. The solid curve is the rate predicted on the basis of the measured ρ_s and $v_{s,c}$ data when R_λ is taken as 5% per decade of time.

sions with Geoffrey Chester, Michael Fisher, and James Langer.

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VORTEX-RING INTERACTIONS IN SUPERFLUID LIQUID HELIUM*

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We have observed interactions between collimated monoenergetic beams of charged vortex rings. The cross section for ring-ring interaction is approximately geometrical, consistent with a hydrodynamic interpretation. Capture of free ions by oppositely charged rings has also been observed.

Several previous experiments involving charged quantized vortex rings have indicated the existence of interactions among them. We have studied this phenomenon as a function of ring energy and find a cross section which, like the energy dependence of ring velocity[1] and size,[2] supports the idea that the ring can be described by classical equations supplemented by quantization of circulation and a core radius of atomic dimensions.

Our experiments were all performed in cells immersed in superfluid helium cooled by a He^3 refrigerator capable of maintaining the (400-cm^3) volume below 0.3°K. Several different interaction cells were used[3]; the most successful of these is illustrated in Fig. 1. In this apparatus, identical Po^{210} radioactive sources, grids, colli-

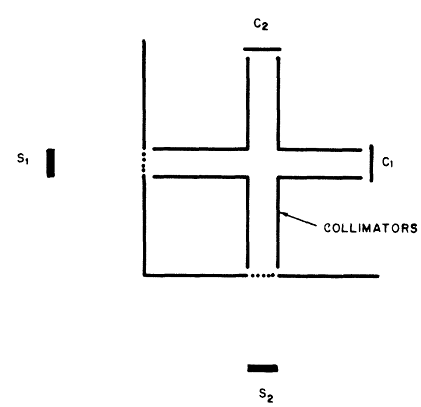

FIG. 1. The experimental cell. S_1 and S_2 are the radioactive sources; C_1 and C_2, the corresponding collectors.