TEMPERATURE DEPENDENCE OF THE SUPERFLUID HEALING LENGTH

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The reduction in superfluid mass of helium contained in restricted geometries has been studied as a function of temperature. The results are discussed in terms of a superfluid healing length ξ_s. Near T_λ, ξ_s can be described by a power law, $\xi_s = \xi_{s,0}(1-T/T_\lambda)^{-\nu}$, where $\nu = 0.67 \pm 0.04$. A value for $\xi_{s,0} = 4.0 \pm 0.5$ Å is obtained from the analysis of superfluid flow through a slit of known geometry.

The properties of superfluid helium are affected markedly when the dimensions of the system are restricted, for instance, the helium film or helium contained in fine pores.[1] In this paper we report quantitative measurements of the reduction of the superfluid mass for liquid helium contained in various types of restricted geometries. Such a reduction in the superfluid mass has been reported before. Clow[2] observed near the transition temperature T_λ, using a persistent-current method, that the average superfluid density for helium in nominal 2000-Å pores was reduced by an amount equivalent to a shift of 0.75 mK in T_λ. Rudnick and co-workers[3] and Brewer et al.[4] using fourth sound have studied the reduction at lower temperatures for helium contained in packed powders and porous Vycor glass. More recently, Rudnick et al.[5] and Kagiwada et al.[6] have reported the reduction of ρ_s in unsaturated helium films, using third sound. Henkel, Kukich, and Reppy[7] have made measurements of ρ_s in unsaturated films using persistent-current methods.

Although these experiments show clearly the qualitative effect of the reduction of the superfluid mass, only the film experiments have yielded quantitative information because of the uncertainties of the geometry in the porous systems. In the film experiments, however, there remains an uncertainty since the solid and free surface may have quite different effects.

We have employed a new technique in our study of the reduction of the superfluid mass in unsaturated helium films. A persistent current is formed in an unsaturated film[7] of thickness D. The angular momentum L_p of the persistent current is a function of the temperature, the superfluid velocity, and the thickness of the film. In this experiment the temperature is held constant and the thickness of the film is increased by carefully condensing additional helium gas on the unsaturated film. The result is a crystallike growth of the superfluid state with the additional liquid assuming the same superfluid velocity field as the liquid already present. An increase in D, then, produces an increase in L_p proportional to the change in thickness and the superfluid density of the added mass. Figure 1 shows the results of such a measurement made at a temperature of 1.39 K. The angular momentum L_p is plotted against the total thickness of the film.[8,9] We assume that a solid layer about 3.6 Å thick is produced by the van der Waals attraction of the wall.[9]

The important features of the data are the linear increase of L_p with D and the nonzero intercept D_0. Since it is known that average superfluid density of a film approaches that of bulk helium as the thickness increases, the linear increase of L_p with thickness implies that additional mass contributes to the superfluid with essentially the bulk value of superfluid density. The value of D_0 is a measure of how much the total superfluid mass has been reduced in the film. Since this ex-

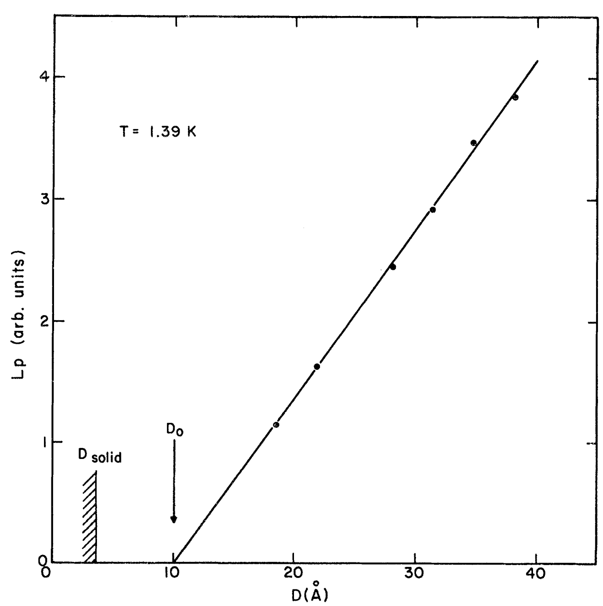

FIG. 1. The angular momentum L_p of a persistent current formed in an unsaturated helium film is shown as a function of the thickness D of the film. The angular momentum is observed to grow in a linear fashion as the thickness is increased.

periment shows that D_0 is independent of the film thickness for the range of thickness involved here, we may conclude that the reduction in the superfluid mass is a surface rather than volume effect. Thus at a given temperature we expect an extra contribution to the normal fluid mass by an amount proportional to the surface area.

It is convenient to discuss the data in terms of a temperature-dependent length, $\xi_s(T)$, defined by equating the product $\rho_s\xi_s$ with the additional normal-fluid mass (neglecting the solid layer) per unit area. In Fig. 1 the length ξ_s is equal to D_0-D_{solid} and measures an effective "healing length" for the reduction of ρ_s near the wall.

The measurement described above may be repeated at different temperatures to determine the temperature dependence of ξ_s. The length $\xi_s(T)$ may also be determined from the temperature dependence of the angular momentum of a persistent current in a film of known thickness and the value of ξ_s at a single temperature. The angular momentum of a persistent current formed in helium-filled channels of Vycor glass or other porous material can be analyzed in a similar way to yield estimates of $\xi_s(T)$.

At present, because of experimental difficulties, it has not been possible to make measurements on films of controlled thickness much above 2.0 K. However, the whole temperature range from 1.1 K to T_λ is accessible to persistent-current measurements in filled channels. A number of different porous materials are used to provide a range in channel size from the 20-Å radius of porous Vycor glass to filter materials with pores on the order of several thousand angstroms. One gains the advantage that there is no uncertainty arising from the presence of a free surface. However, this is balanced by a loss of knowledge about the actual geometry. In spite of geometrical uncertainties the persistent-current studies can determine accurately the temperature dependence of $\xi_s(T)$, especially near the transition provided ξ_s is small compared with pore radius.

In order to obtain a better measure of actual magnitude of $\xi_s(T)$ we have employed a new method for the determination of the superfluid density near the transition. A careful measurement was made of the critical mass-transfer rate under a gravitational head through a slit formed by two concentric stainless steel cylinders.[10] The transfer rate was observed to change by a factor of 10^4 as the temperature was varied over a range from $T_\lambda-0.5$ mK to 1.5 K. The data are analyzed under the assumption that the superfluid critical velocity is controlled by a thermal activation process[11,12] where the main temperature dependence in the free-energy barrier separating flow states is determined by the average superfluid density $\langle\rho_s\rangle$ in the slit. This assumption has been used successfully to predict the temperature dependence of the decay of persistent currents from independent measurements of $\langle\rho_s\rangle$ and the critical velocity.[12] In the present analysis a free-energy barrier is determined which is similar in form to barrier functions controlling the critical velocity of persistent currents where, near the transition, the critical velocity becomes proportional to the superfluid density.[2,12] The analysis produces a value for $\langle\rho_s\rangle$ to within a constant factor. This factor may be obtained by normalization at low temperature since $\langle\rho_s\rangle$ is related to bulk ρ_s by $\langle\rho_s\rangle=\rho_s[1-2\xi_s/D]$, where D is the average slit width. The film data place an upper bound on $\xi_s\ll D$, at low temperature, so, for large geometries such as the slit or larger pore sizes, the choice of normalization constant is restricted to the point where the values of $\xi_s(T)$ near the transition are little affected.

The average spacing of the slit has been determined to be 3850 ± 100 Å by the observation of U-tube oscillations through the slit[13] at temperatures near 0.6 K. Using this value for the slit width we have plotted ξ_s against reduced temperature $\tau=(1-T/T_c)$ in Fig. 2. The estimates of ξ_s from measurements in the two larger pore sizes are adjusted to fit the slit data near the transition. The Vycor data are normalized using the measured (Hg intrusion) pore diameters of 20 Å and the film value of $\xi_s(1.39\text{ K})=6.6$ Å. This value assumes that only the solid boundary contributes to enhanced normal fluid mass. This assumption seems to give a more consistent agreement between the various sets of data although the question should not be considered closed.

Kuper[14] has suggested a mechanism for an increase in normal density near the wall caused by a reduction in the roton energy due to the wall. This effect is of the right order of magnitude possibly to explain the data below 2.0 K. However, at present the theory is in only a rough form and a detailed comparison with experiment is not possible. In Kuper's theory the influence of the wall falls off quite rapidly and hence it is unlikely that this explanation is applicable near the transition where ξ_s becomes of the order of hundreds of angstroms.

Another possible contribution to the added nor-

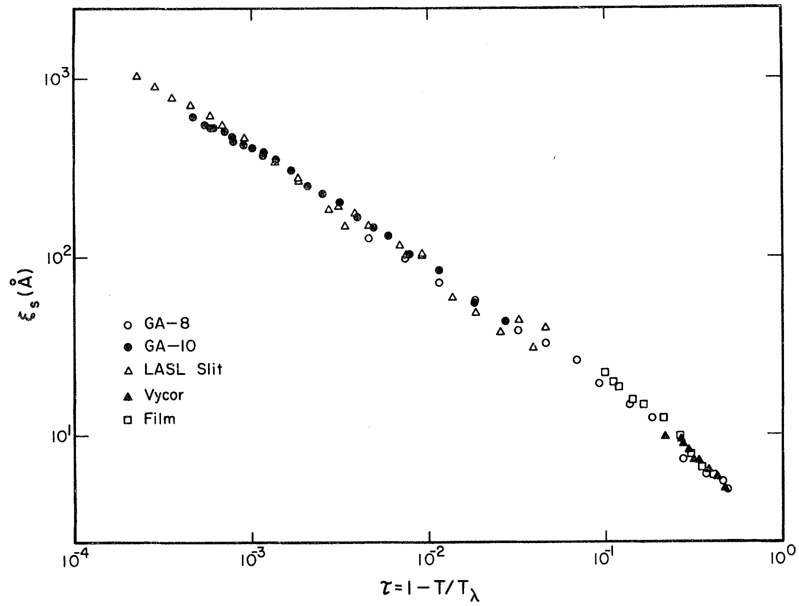

FIG. 2. The superfluid healing length ξ_s is shown as a function of reduced temperature $\tau = 1 - T/T_\lambda$. The data for the filter materials GA-8 (nominal 500 Å) and GA-10 (nominal 2000 Å) are normalized by a constant factor to achieve a good fit to the slit data.

mal mass may result from the negative slope of the λ line in the pressure-temperature diagram and the existence of a strong pressure gradient near the wall due to van der Waals attraction. However, an estimate of this effect indicates that it can account for only a small fraction of the length ξ_s near T_λ.

The phenomenological theory of Ginzburg and Pitaevskii[15] and Mamaladze[16] discusses the behavior of the superfluid density near a boundary in terms of a temperature-dependent length calculated to be $l(\tau) = 1.63\tau^{-2/3}$ Å. For our geometries the theory would predict $\xi_s \simeq \sqrt{2} l$.

The data shown in Fig. 2 near the transition ($\tau < 0.05$) can be fitted with a power law $\xi_s(\tau) = \xi_{s,0}\tau^{-\nu}$, where $\xi_{s,0} = 4.0 \pm 0.5$ Å and $\nu = 0.67 \pm 0.04$. Since recent measurements[17] of the bulk superfluid density have shown that ρ_s varies as $\tau^{2/3}$, we see that within experimental error near the transition $\xi_s \propto \rho_s^{-1}$ in agreement with the Ginzburg-Pitaevskii-Mamaladze theory. However the coefficient $\xi_{s,0}$ obtained from the analysis of the critical flow measurements is almost twice as large as that estimated from the theory.[16]

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STARK BROADENING OF TWO IONIZED-HELIUM LINES BY COLLECTIVE ELECTRIC FIELDS IN A LABORATORY PLASMA*

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Profiles of the He II 4686- and 3203-Å lines observed during the passage of the imploding current sheath in a high-velocity, low-density θ pinch show a broadening that at early times is not due to the usual mechanisms (Doppler, Holtsmark, or Zeeman effects). Most of this broadening is therefore interpreted as due to Stark effects caused by suprathermal collective field fluctuations, and at later times as due to a combination of these and Doppler effects.

Hydrogen lines and ionized-helium lines, which because of their linear Stark effects are very sensitive to electric fields, have served in numerous experiments and analyses of stellar atmospheres as noninterfering and remote probes for electron (or ion) density determinations. The original theoretical basis of this method was provided by Holtsmark,[1] who realized that N singly charged ions per unit volume would produce "microfields" with typical field strengths not much larger than $F_0 \approx 2.6eN^{2/3}$. He calculated the distribution of these fields, assuming ions to be statistically independent. These distributions behave for large F as $1.5F_0^{3/2}/F^{5/2}$, corresponding to $\sim(\Delta\lambda)^{-5/2}$ wings for lines broadened by linear Stark effects. Holtsmark's theory was later improved by allowing for equilibrium correlations between ions[2] and by inclusion of electron effects.[3] The calculated[3] half-width even of the 3203-Å line (which is most sensitive to Stark effects) from particle-produced fields is near or below 0.1 Å for the electron densities encountered in our experiment ($N \lesssim 7\times10^{13}$ cm^{-3}). Estimated Zeeman effects for the magnetic fields involved ($\lesssim$3 kG) are still smaller, and for ion temperatures $kT_i \gtrsim 2$ eV, Doppler broadening would thus appear to be the dominant broadening mechanism, with the ratio of the half-widths given by the ratio of the wavelengths of the lines.

An implicit assumption in the calculations[3] of Stark broadening had been that particles beyond a Debye radius from the radiators would contribute only very little to the broadening. The fields from these particles correspond to the various plasma waves, whose contributions to the total field are indeed negligible when the plasma parameter is small and when equipartion at the particle temperature extends to the relevant collective modes. In contrast, we report experimental evidence for Stark broadening by collective fields greatly in excess of equipartition values, both to warn against the indiscriminate use of the Holtsmark method and to demonstrate an application of this effect to the investigation of plasma turbulence.

The line profiles were measured end-on when the magnetic structure generated by a fast-rising current in the θ-pinch[4] coil passed through the line of sight (at a radius $r = 12.5$ cm with $\Delta r \approx 3$ cm) into a preheated ($N \approx 10^{13}$ cm^{-3}, $T_i \approx T_e \approx 1$ eV) helium plasma containing a ~0.3-kG magnetic field antiparallel to the driving field. Current densities in the magnetic transition layer as measured with probe coils correspond to electron drift velocities reaching $\sim2\times10^8$ cm/sec or energies of ~10 eV, suggesting very rapid electron heating via the Buneman process[5] to similar temperatures and therefore strong electron-impact excitation of the helium ions. While the underlying electrostatic instabilities are thus more