Measurements Of The Superfluid Fraction Of ^{4}He In 9.4 nm Channels, 19 µm Wide And 2000 µm Long

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Abstract. We report measurements of the superfluid fraction of ^{4}He confined in small channels 9.4 nm high, 19 µm wide by 2000 µm long. This confinement corresponds to a film of finite lateral extent. The data show a shift in the transition to a lower temperature which is larger than the logarithmic dependence expected from finite-size scaling and Berezinskĭ -Kosterlitz-Thouless theory. This shift however is smaller than the one proposed by Sobnack and Kusmartsev for this kind of geometry. When examining the behavior of the shift for confinement at several widths, we found that the shift favors a power law with a larger exponent than predicted by Sobnack and Kusmartsev.

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The superfluid properties of ^{4}He films have been studied extensively for many years. However, the properties of films which in addition are laterally constrained have not been explored in as much detail. We report measurements of the superfluid fraction of ^{4}He confined in small channels 9.4 nm high, 19 µm wide by 2000 µm long. We compare these data to earlier results.

To achieve the film geometry for this experiment, we confine helium between two silicon wafers, 5 cm in diameter, directly bonded at a separation determined by a lithographically-formed pattern of SiO_2. One wafer, with a center hole, is patterned with a 4000 µm wide outer ring, a 2000 µm wide inner ring, and a series of SiO_2 posts which provide a 310.6 nm separation between the two wafers. The outer ring is used to seal the cell and the inner ring defines two reservoirs, one that is immediately below the ^{4}He filling line located at the center of the cell and the other deeper into the cell. The second wafer has radially patterned onto it 72 channels 9.4 nm high, 19 µm wide and 2000 µm long which connect both reservoirs. When these wafers are bonded, the two reservoirs are connected by the narrow channels. Superfluid helium can be driven in resonance across the channels by using a film heater which is deposited on one of the wafers. The resulting temperature oscillations are detected using a biased germanium thermometer. The technique of adiabatic fountain resonance (AFR) has been described previously [1]. The superfluid density is obtained by fitting the frequency response to the excited AFR lineshape.

In Fig.1 we have plotted the superfluid fraction of ^{4}He and dissipation in two different channels. One result corresponds to the 9.4 nm high by 19 µm wide channels and the other corresponds to 10 nm high by 8 µm wide channels previously measured [2].

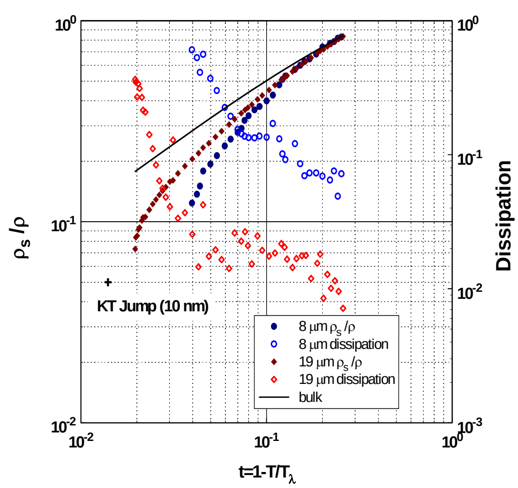

FIGURE 1. Superfluid fraction and dissipation of ^{4}He confined in two different films of finite lateral extent as function of the reduced temperature $t=1-T/T_\lambda$.

The cross indicates the expected Berezinskĭ-Kosterlitz-Thouless (BKT) transition [3,4] for the superfluid fraction. The temperature (T_c) at which the transition should take place is based on the behavior of the superfluid onset for planar films of effectively infinite lateral extent. This temperature is well described by the exponent ν expected from the 3D correlation length as $t_c=(1-T_c/T_\lambda)\sim L^{-1/\nu}$. Furthermore, given the behavior of the 2D correlation length, and finite-size scaling, one expects that there would be a further shift given by $\Delta t_c=[T_c(L,\infty)-T_c(L,W)]/T_c(L,\infty)= [2\pi/b\ln(W/\xi_o)]^2$ where ξ_o is the effective vortex core radius and b, a non-universal constant. We have estimated this shift to be of the order of 2×10^{-4} for these sets of data. However, we observed that, for both channels, the value of t_c at which the transition occurs is shifted to a much lower temperature than expected from finite size-scaling and BKT. This shift is larger for the 8 μm wide channels than for the 19 μm wide ones. This experiment, in addition to previous data obtained in our laboratory for 2D finite films [2,5], supports the idea that there is a new class of transition for thin films of finite lateral extent as predicted by Sobnack and Kusmartsev [6]. Their theory states that, for this kind of films, the shift in t_c should behave as a power law such that $\Delta t_c=(2\xi_o/W)^{1/2}$. This power-law behavior has not been confirmed yet for superfluid films. But, there is some suggestion from our most recent and preliminary data [7], in addition to the ones presented in this paper, that the power is larger than 1/2. These data corresponds to 9.4 nm channels with varying width (3 μm, 5 μm and 10 μm). By plotting the corresponding shift of the superfluid onset temperature versus the width of the channels and doing a least square fit, our data are *best represented by a power of 1.4±0.1.*

In general, one could argue that it is the dissipation which prevents ρ_s from reaching its expected value. But that is not the case. The general trend of the dissipation is that, far away from the transition, it slowly increases as one moves towards the transition, and then there is a sudden rise as the transition is approached. The rapid rise of the dissipation as ρ_s vanishes is qualitatively consistent with the intrinsic mechanism associated with vortex-pair unbinding characteristic of the two-dimensional superfluid. We studied the effect on the resonance frequency ω_o as a function of excitation power in the heater. We observed, as shown in Fig. 2, that there is a mild dependence of ω_o on power. Far from the transition, ω_o decreases with increasing power. Closer to the transition this is reversed. Within this trend, one could reasonably extrapolate to ω_o at zero power. The data of ρ_s plotted in Fig. 1 were obtained at 0.12 μW. Extrapolating to zero power would affect the values by ~2%. This is smaller than the size of the symbols used in the figure.

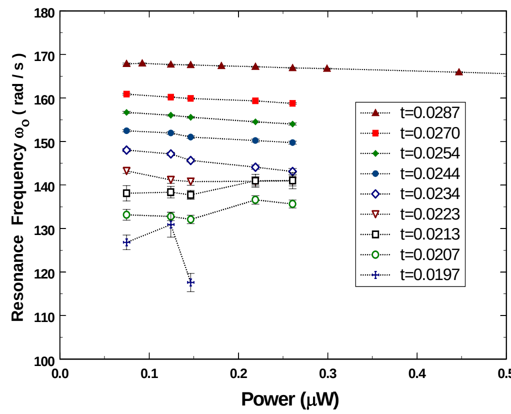

FIGURE 2. Resonance angular frequency plotted as function of power. The error bars represent the uncertainty with which the resonance frequency can be obtained from the signal's lineshape.

This new study supports the fact that in laterally confined 2D films the superfluid transition is shifted to lower temperatures than expected from BKT theory. However, it cannot verify the power-law behavior predicted by the Sobnack-Kusmartsev theory.

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