Surprising behavior of the superfluid fraction for ^{4}He and ^{3}He-^{4}He mixtures in 18.5 nm channels.

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Abstract

We have obtained the superfluid fraction of ^{4}He and mixtures confined in channels $0.0185\mu\text{m}\times1.08\mu\text{m}\times\infty$. We compare this with film data $\text{L}\times\infty\times\infty$, and data for channels $0.0483\mu\text{m}\times3.0\mu\text{m}\times\infty$. The behavior of the data in the smallest channels is quite different from what one might expect for a planar film of a given thickness. The transition is shifted to a lower temperature than expected; and, the overall behavior of ρ_s does not follow the trend observed with other confined films. This suggests that the lateral dimension plays a significant role in the behavior. We believe our observations are consistent with the recent proposal of Sobnack and Kusmartsev about a new mechanism for vortex unbinding in 2D films.

Key words: superfluid density; finite-size scaling; confined helium; helium mixtures

The critical behavior of a finite system presents a number of challenges in understanding and interpretation. Unlike systems in the thermodynamic limit, the behavior of finite systems depends on the geometry. It is only in simple situations that one can describe such systems via universal scaling functions. We have measured both the heat capacity and the superfluid density ρ_s of helium near the superfluid transition when confined in a film geometry between wafers of silicon [1]. These data show that the expected scaling of the *heat capacity* works everywhere except in the region near and below the transition in the film. This failure of scaling is also evident in the superfluid fraction[2]. The scaling behavior of these films can be understood as that of a system behaving 3-dimensionally, 3D, far from the transition and crossing over to 2D as the 3D correlation length increases. This picture assumes that the lateral dimension of the film is effectively infinite. If one makes the lateral dimension finite, then one can expect that instead of 2D crossover one will have crossover into *finite-size* 2D. We believe we have seen this in recent measurements of ρ_s.

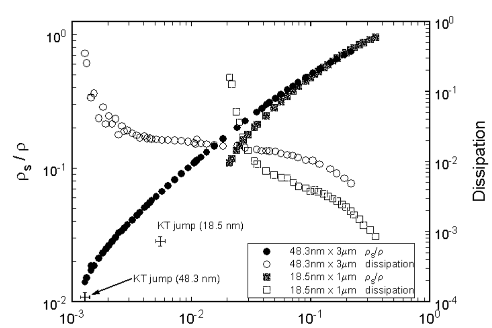

Fig. 1. Superfluid fraction and dissipation as obtained from AFR.

The experimental arrangement for these measurements consists of channels 18.5 nm high, 1μm wide and 0.2 cm long. These connect a reservoir of bulk helium and an array of 1 μm^3 boxes. The design of this cell was intended for the measurement of the heat capacity of the helium confined to the boxes [3]. However, using the technique of Adiabatic Fountain Resonance [4] we

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were able to obtain the superfluid fraction of the *helium in the connecting channels*. In these measurements the helium in the boxes is already superfluid, thus, one may simply consider it as a reservoir for the oscillation of the superfluid from the boxes through the channels into the bulk helium reservoir of the filling line. In another experiment we have also measured the superfluid fraction of helium in channels 48.3 nm high, 3 μm wide and 0.5 cm long [5]. The superfluid fraction for these two channels is shown in Fig. 1. Also in this figure are plotted the dissipation in the resonance signal[4]. The two plusses on this plot indicate the jump in ρ_s as expected for 2D films on the basis of the Berezinskii-Kosterlitz-Thouless theory [6,7]. The temperature at which these jumps should take place is taken from the behavior of T_c on the basis of 3D correlation-length scaling (see below). One can see that ρ_s for the 48.3 nm channels vanishes close to the expected value, while the smaller channel (and smaller width) miss both the expected jump and the shift in transition temperature. The rise in dissipation close to T_c is quite similar for these data. Thus, it is not the dissipation which prevents ρ_s from reaching its expected value.

In Fig. 2 are plotted the superfluid onset temperature for planar films of effectively infinite lateral extent. The shift in transition temperature with film thickness is described well by the exponent v expected from the 3D correlation length $(T_\lambda - T_c)/T_\lambda \sim L^{-1/v}$. The value of T_c for the 18.5 nm channels, both for ^{4}He and for four mixtures, are well away from this line. Notice, as well, that the mixtures for the 48.3 nm channels are also somewhat removed from the expected trend. Different values of L are assigned to the mixtures because their 3D correlation length is larger[5]. It seems likely that the anomolous behavior of the smallest channels, relative to their expected position on the straight line, is dictated by their finite lateral extent. One might not expect this on the basis of the 2D correlation length $\xi_{2D} = \xi_0 e^{2\pi/bt^{1/2}}$, where ξ_0 and b are constants, and t is the reduced temperature *measured from the 2D* T_c. This function diverges exponentially and predicts a further shift in the t_c of finite 2D films of width W=1 μm of $[2\pi/b\ ln(W/\xi_0)]^2 \approx 4 \times 10^{-4}$, where we have used 2.5 nm for ξ_0, and b= 50 [8]. This shift is much smaller than the observed shift from the solid line of $\approx$0.016, as can be seen in Fig. 2 for $x = 0$. However, recently there has been a prediction by Sobnack and Kusmartsev (SK) that the process of vortex unbinding for a film of *finite lateral extent* should actually be a power law, rather than logarithmic[9]. This is due to the mechanism of vortex generation at a boundary. This preempts the transition expected on the basis of the BKT theory of vortex antivortex unbinding. Accordingly, one would expect a shift in t_C of a film due to finite lateral size W to be given by $t_C = (2\xi_0/W)^{1/2}$[9]. This agrees with the measured shift of 0.016 if one takes $\xi_0 = 0.1$ nm, and yields 0.07 if one takes $\xi_0 = 2.5nm \sim \xi_{3D}(T_C)$ as one might expect for a 18.5 nm thick film. Thus, we believe our measurements support the SK picture for the transition of a film of finite lateral extent. However, further measurements with channels of varying W and smaller L will be necessary for a quantitative verification of the theory.

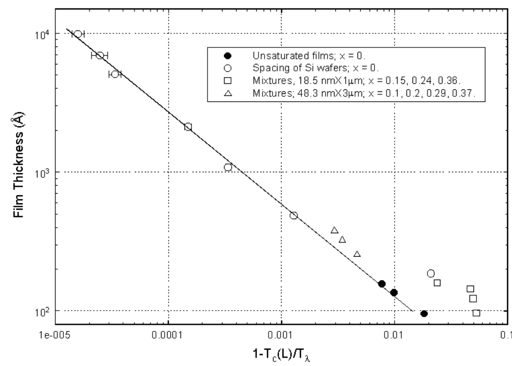

Fig. 2. Film thickness as function of shifted tansition temperature. Note that the smallest films of finite lateral size, 18.5nm $\times$ 1μm are well removed from the solid line.

Acknowledgements

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