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 $0.0185 \mu m \times 1.08 \mu m \times \infty$. We compare this with film data $L \times \infty \times \infty$, and data for channels $0.0483 \mu m \times 3.0 \mu m \times \infty$. 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 $\rho_s$ 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 $\rho_s$ 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 $\rho_s$.

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

The experimental arrangement for these measurements consists of channels 18.5 nm high, 1$\mu$m wide and 0.2 cm long. These connect a reservoir of bulk helium and an array of 1 $\mu$m$^3$ 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...
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 $\rho_s$ 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 $\rho_s$ 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 $\rho_s$ 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 $\nu$ expected from the 3D correlation length-scaling (see below). One can see that $\rho_s$ 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 $\rho_s$ from reaching its expected value.

with the measured shift of 0.016 if one takes $\xi_0 = 0.1$ nm, and yields 0.07 if one takes $\xi_0 = 2.5$nm $\sim \xi_{3D}(T_c)$ 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.

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References