Behavior of ^{4}He Near T_λ in Films of Infinite and Finite Lateral Extent

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We report studies of a ^{4}He film confined between two silicon wafers separated by 3189 Å. The film is connected to a bulk helium reservoir via small channels 100 Å high, 8 μm wide by 2000 μm long. This cell design has allowed us to study the heat capacity in a planar confinement (a film of ∞ lateral size), and the superfluid density in the connecting channels (a film of finite lateral size). This work is relevant to finite–size scaling of the specific heat for 2D confinement and it is compared with earlier data. It is also relevant to finite–size 2D behavior for the superfluid density which is related to the recent theory of Sobnack and Kusmartsev. Analysis of the data is presented as well as a discussion of future cell designs to address, in particular, the behavior of laterally confined films.

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1. INTRODUCTION

The study of effects of confinement on systems which exhibit a second order phase transition has been the subject of long–standing interest. The critical behavior of these systems is characterized by the divergence of the correlation length ξ as the system approaches the transition temperature. When this length becomes comparable to the size of the smallest dimension in the system, *finite–size effects* can be observed in thermodynamic properties such as heat capacity or superfluid density (in the case of ^{4}He). The magnitude of these effects depends on the confinement size L, boundary conditions and the lower crossover dimension of the confined system. Both the heat capacity and the superfluid density measurements are used to test scaling predictions.[1] In this work, we report studies of the heat capacity of ^{4}He in a 2D confinement (a film of ∞ lateral size), and the superfluid density in the connecting channels (a film of *finite lateral* size). The latter results are preliminary to future work in which the lateral size will be varied systematically.

2. EXPERIMENTAL DETAILS

To study finite–size effects in ^{4}He near its superfluid transition temperature, we confine helium between two silicon wafers. The design of the present cell consists of two silicon wafers (2″ diameter and 0.010″ thick) which have a SiO_2 pattern formed lithographically. One wafer, with a center hole, has as a pattern an outer ring border used to seal the cell and a series of SiO_2 posts which provide a 3189 Å separation between the two wafers. A disk of unpatterned SiO_2 is left in the center of this wafer. To complete the cell, a second wafer is directly bonded to the first. This second wafer has patterned onto it channels 100 Å high, 8 μm wide and 2000 μm long. These channels, at the center of the wafer, connect the filling line and 3189 Å film. We used an AFM to measure the uniformity and profile of the channels over different areas of the wafer. We found that the width of the channels was not as uniform as desired. Local variations in width were about 10%. This is a problem with the lithographic process which will be solved in future cells. Details of the construction of similar cells and the experimental setup have been reported.[2] The present cell design has allowed us to study the specific heat of the 3189 Å film of infinite lateral size, and the superfluid density in the connecting channels which define the *film of finite lateral size*. The specific heat is measured using a modified AC technique[2,3] where an AC voltage is applied across the terminals of a heater evaporated on the cell bottom while the average temperature of the cell is held constant. This causes temperature oscillations of the confined helium which are detected by a thermometer placed on the top of the cell. These temperature oscillations are inversely proportional to the heat capacity of the sample. The superfluid density of the helium confined in the connecting channels is obtained by using the Adiabatic Fountain Resonance (AFR) technique.[4] The two "reservoirs", the film of 3189 Å and the filling line, connected by the channels are already superfluid in the temperature range where we perform the measurement of the superfluid fraction of the helium in the channels. When the helium in these channels becomes superfluid at a temperature below T_λ, one can drive, in resonance, an oscillation from the wafers into the filling line via the channels. This resonance is driven and detected thermally with the restoring force provided by the compressibility of the helium. The square of this characteristic resonance frequency is proportional to ρ_s/ρ.[4]

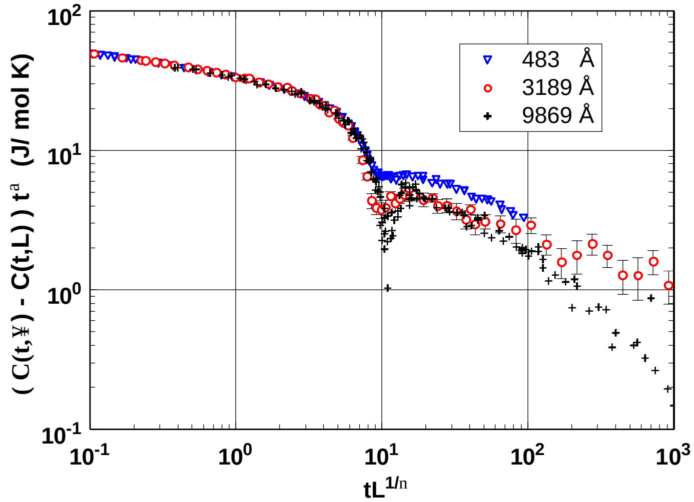

Fig. 1. A scaling plot for the specific heat region $T < T_\lambda$.

3. DATA ANALYSIS

3.1. Specific Heat of 3189 Å Film in 2D Planar Confinement

In this section we report measurements of the specific heat of a 3189 Å helium film to test scaling predictions near the superfluid transition.[1] These new data are an addition to the six different confinement sizes, which we have previously measured, ranging from L = 483 Å to 9869 Å.[2,5] These data are analyzed to check the behavior expected from correlation–length scaling. The data may be scaled using the following equation[2]

$$[C(t,\infty) - C(t,L)]t^\alpha = (tL^{1/\nu})^\alpha f_2(tL^{1/\nu}) \tag{1}$$

where α and ν are the heat capacity and correlation length critical exponents. It has been found, from the earlier work done in our laboratory, that the specific heat scales well for temperatures above T_λ and the region immediately below it. The present data agree with this. However, near the specific heat maximum, deviations from scaling have been seen. The present data give strong support to the earlier conclusion[2,5] that scaling fails for $T < T_\lambda$ as shown in Fig. 1. In this figure, starting from the smallest confinement, one can see that the region of the specific heat maximum (seen here as a minimum in this difference plot) develops a small dip. As one moves to larger confinements this dip becomes much more pronounced. Also, one can notice that the superfluid region where $tL^{1/\nu} > 12$ (slightly to the right of the minimum) does not scale; the 3189 Å confinement data fall between the two other confinements. This *lack of scaling* continues for larger values of $tL^{1/\nu}$. It is possible that this lack of scaling is due to the system crossing

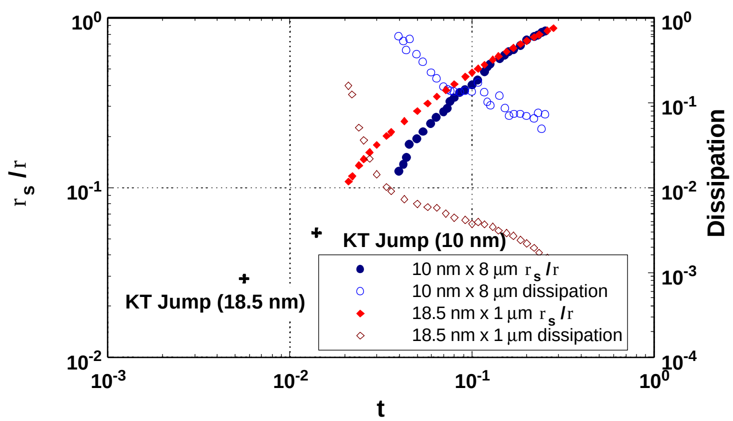

Fig. 2. Superfluid fraction and dissipation for 2D finite film obtained from AFR.

into a 2D regime behavior. In 2D it is known, that for a XY system, the transition is not universal.[6] Perhaps we are seeing a manifestation of this.

3.2. Superfluid Density of 100 Å Film in 2D Finite Confinement

In Fig. 2. we present the results obtained for the superfluid fraction of ^{4}He in the finite 2D channels. We compare this with our earlier data for a similar confinement[7]. The dissipation in the resonance signal is plotted as well. The crosses indicate the Berezinskǐ–Kosterlitz–Thouless (BKT) transition.[8,9] This manifests itself as a discontinuity (jump) in the superfluid fraction. The temperature at which this jump should take place is taken from the behavior of T_c (the superfluid onset) on the basis of the 3D correlation–length scaling. We note that, for both channels, the transition temperature where ρ_s/ρ vanishes is shifted to a lower temperature than would be expected on the basis of BKT theory. Also, both data miss the magnitude of the KT jump. We believe that both the temperature at which ρ_s/ρ vanishes and the magnitude ρ_s/ρ are indicative of the finite lateral size of the films.

We have plotted in Fig. 3. the superfluid onset temperature for planar films of effectively infinite lateral extent which is described well by the exponent ν expected from the 3D correlation length as $t_c = (1 - T_c/T_\lambda) \sim L^{-1/\nu}$ represented by solid line. However, the value of t_c for the 10 nm channels and the 18.5 nm channels deviates from this locus. The behavior of these shallow channels, relative to their expected position on the straight line,

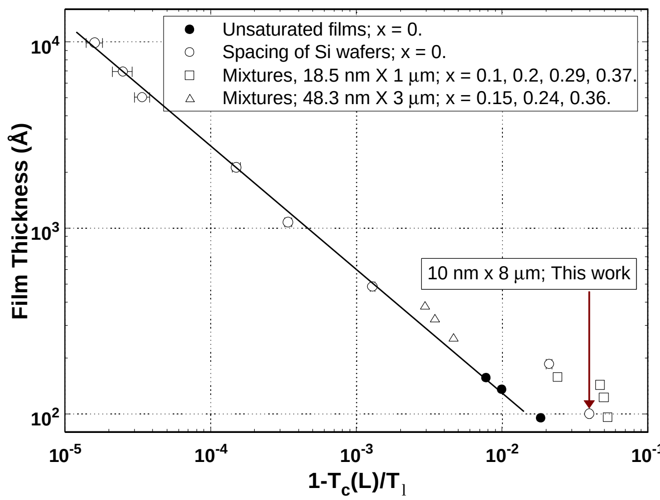

Fig. 3. Film thickness as function of the shifted transition temperature. Note that the smallest films of finite lateral size 10 nm $\times$ 8 μm and 18.5 nm $\times$ 1 μm are well removed from the solid line expected from the 3D correlation length.

suggests that their finite lateral extent (8 μm and 1 μm respectively) plays a significant role in their behavior. To have a quantitative description of our present results, we analyze this behavior on the basis of the 2D correlation length and the new theory of single vortex unbinding in 2D films proposed by Sobnack and Kusmartsev.[10] The BKT theory predicts a further shift in the t_c of the 2D films of finite lateral width W given by $\Delta t_c = \left[\frac{2\pi/b}{ln(W/\xi_o)}\right]^2$ where ξ_o is the effective vortex core radius and b is a nonuniversal constant. For W=8 μm, using $\xi_o = 31$ Å and $b = 50$ from Ref. 11, we calculate $\Delta t_c \approx 2.6 \times 10^{-4}$, which is much smaller than the observed shift from the solid line ≈ 0.026 as can be seen in Fig. 3. On the other hand, the Sobnack–Kusmartsev theory predicts, for films of finite lateral extent, that the shift in t_c should go as a power law, namely, $\Delta t_c = (2\xi_o/W)^{1/2}$. This shift is associated with the spontaneous generation of single vortices and antivortices near the boundaries in confined superfluid systems. Using the values from our data in this new prediction, we obtain that $\Delta t_c = 0.028$, which agrees with the measured shift of 0.026. Thus, we believe that our measurements from this work support the idea that there is a new class of transition for shallow films of finite lateral extent and that our data supports the Sobnack–Kusmartsev picture for this transition. Our goal, for future work, is to do a complete study of these 2D finite systems by doing a systematic variation of the width of the channels, keeping the height of the channel fixed at 100 Å for a quantitative verification of the theory. The design of the new cells will consist of two silicon wafers, 2″ in diameter and 0.015″ thick which have a SiO_2 structures patterned lithographically. We will use these thicker wafers since their overall flatness is ~ 2 Å/μm^2 which will allows us to have a uniform separation inside the channels. For distances of ~ 20 μm, the peak variation is no more than 10 Å $\pm$ 2 Å, which is almost a factor of two better compared with 0.010″ wafers. One wafer, with a center hole, will have as a pattern an outer ring border and a series of SiO_2 posts providing a separation of ~ 3500 Å between wafers. A ring 4 mm wide of unpatterned SiO_2 is left 4 mm away from the center. The second wafer will have radially patterned 72 channels 100 Å high, 4000 μm long and the width will be varied for each measurement from 2 to 16 μm. These channels connect the filling line and the 3500 Å film. This design allows us to control the number of channels connecting both "reservoirs". This will improve the signal and, more importantly, define the length of the channel more precisely.

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