Specific Heat of ^{4}He Confined in Channels of 1 μm Square Cross-Section

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We report measurements of the specific heat near the superfluid transition of ^{4}He confined in uniform channels of 1 μm square cross-section. This system undergoes a crossover from three dimensional behavior (3D) to 1D as the transition is approached. This results in a substantial rounding of the specific heat maximum as well as a shift to colder temperatures relative to the bulk system. We compare these data to previous measurements where crossovers from 3D to 2D and 0D were studied with the smallest confining dimension being the same (1 μm) in each case. We also compare these results in the context of finite-size scaling to previous studies where crossover to 1D was measured in cylindrical geometries. We identify regions where surface and edge effects dominate the specific heat, and compare these amplitudes to theory, where available. The realization of the confining geometry in this work is achieved with a combination of silicon lithography and direct wafer bonding.

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1. INTRODUCTION

The behavior of confined ^{4}He near the the superfluid transition has been a subject of interest for some time. Striking deviations of the specific heat from bulk behavior are observed when the correlation length ξ becomes of the same order as the smallest confining dimension L, thereby limiting the extent of spatial fluctuations. Although finite-size effects are inherently shape-dependent, theory predicts that one should be able to scale the specific heat with the ratio ξ/L for equivalent confinements.[1]

We have measured the specific heat of confined helium in films, channels, and boxes where the smallest confining dimension was 1 μm. This corresponds to crossover from three dimensional behavior (3D) to 2D, 1D, and 0D, respectively. These data allowed us to assess the role of the lower dimension in finite-size behavior.

2. EXPERIMENTAL

Our experimental cell consists of a 1 μm thick oxide, thermally grown on a 5 cm diameter silicon wafer. The oxide is then patterned lithographically with 1 μm wide by 4 mm long channels spaced with a 2 μm period. The total length of channels on the cell is approximately 0.5 km. A second, unpatterned wafer is directly bonded to the first, enclosing the channels, and completing the cell. Helium is introduced into the cell through a small ($\sim$0.5 mm) hole drilled in the unpatterned wafer.

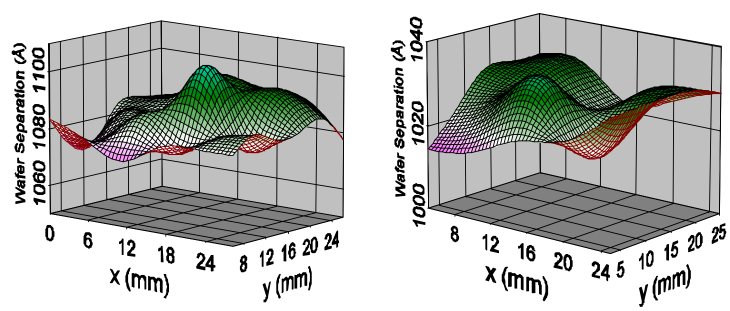

Fig. 1. "Surface of separation" for the box (left) and channel (right) geometries measured via infrared interferometry. The uniformity of separation is about 1%.

Details of the 0D and 2D cell geometries have been previously reported.[2,3] The 2D cell is made from two silicon wafers spaced uniformly apart by a number of small oxide posts. The spacing between posts is on the order of 1 mm which is macroscopic compared to the correlation-length ξ. The 0D cell contains some 10^9 boxes etched into the oxide. This cell is unique in that the boxes are filled by 18.5 nm high by 1 μm wide channels patterned onto the top wafer. Due to finite-size effects, the helium in these channels remains *normal* when the liquid in the boxes becomes *superfluid*. This cell is therefore a collection of uncoupled boxes.

The uniformity of the wafer spacing is measured after the bonding process via infrared interferometry. Deviations from the average separation are typically less than 10 nm across the diameter of the cell. Fig. 1 shows interference data for the 0D and 1D cells. A series of measurements across the face of the cells define a surface of separation which is shown in this figure. Further information on the techniques of cell construction can be found in a number of publications.[4,5]

The cell is staged on a cryostat such that it is weakly coupled to two isothermal stages. A thin-film heater evaporated onto the cell provides for an additional degree of temperature regulation as well as an oscillating heat current for ac calorimetry. The magnitude of the induced temperature oscillations is detected by one of two germanium thermometers attached to the cell.

A small amount of liquid remains in the fill-line. This provides us with a reference for the bulk transition temperature.

3. RESULTS AND ANALYSIS

Fig. 2 shows specific heat for all three dimensionality crossovers plotted as a function of $t = |(T - T_\lambda)|/T_\lambda$. The left and right plots are for $T > T_\lambda$ and $T < T_\lambda$, respectively. The solid black lines represent the bulk behavior.

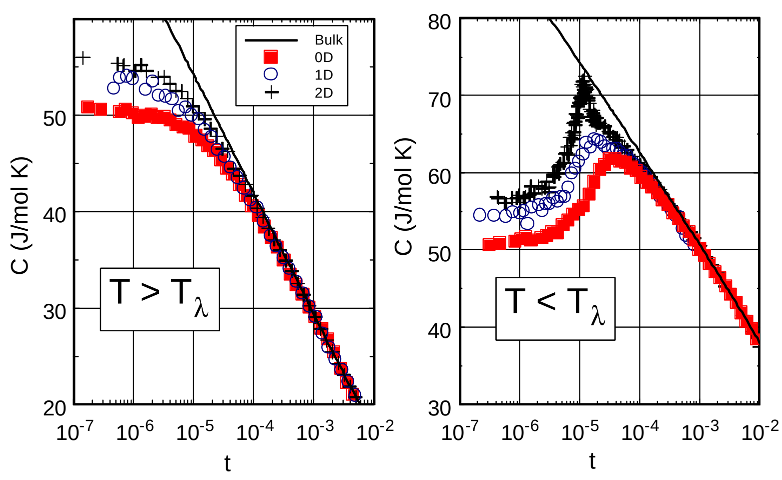

Fig. 2. Specific heat near the superfluid transition of helium confined to a film of thickness L, channels of cross-section LxL, and boxes LxLxL all with $L = 1\mu$m.

One can see that dimensionality has a pronounced effect on the shape of the specific heat maximum, as well as its position in reduced temperature relative to the bulk transition. There is a systematic decrease in the height of the maximum with decreasing dimensionality. Further, the shift to colder temperatures becomes greater with greater confinement

One expects a finite system confined uniformly to a small spatial dimension L to obey a scaling law[6] which can be cast in the form,

$$[C(t,\infty) - C(t,L)]t^{\alpha} = \Delta C t^{\alpha} \equiv g_2(x) \quad (1)$$

The scaling variable $x = tL^{1/\nu}$ is proportional to $(L/\xi)^{1/\nu}$. We use $\alpha = -0.0115$ and $\nu = 0.6705$ as the critical exponents for the specific heat and correlation length, respectively.[7] $C(t,\infty)$ is the bulk specific heat, so the left side of Eq, 1, apart from the factor of t^{α}, is simply the difference between the specific heat of the bulk and confined systems. The function $g_2(x)$ defines a universal scaling function onto which the data are predicted to collapse.

Numerous experimental studies, as well as theoretical calculations have been done for planar geometries. The experimental data have been found to collapse for a wide range of confinement sizes at temperatures above the bulk transition. However, in the vicinity of the heat capacity maximum, and colder, the data do not obey Eq. 1.[5]

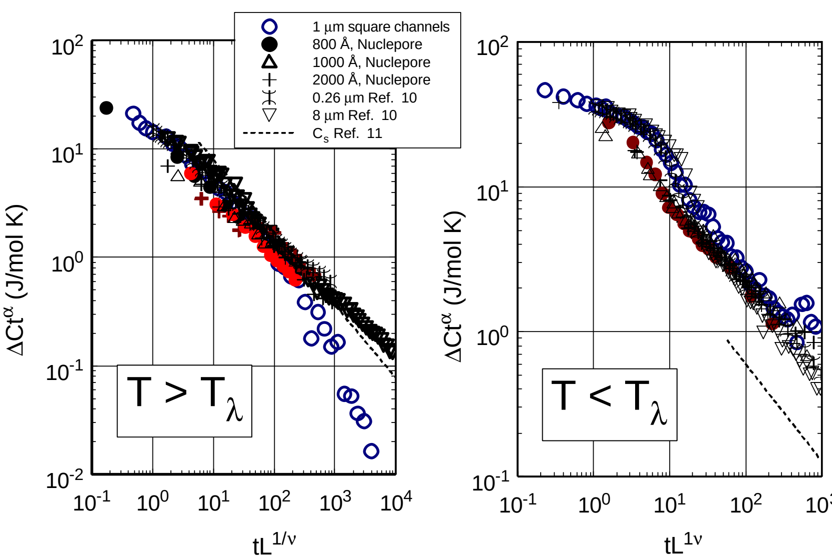

Fig. 3. Data plotted in scaling form according to Eq. 1. If scaling holds, one would expect the data to collapse on universal locus.

We can cast the data for the 1D channels in scaling form, and compare them to earlier measurements of helium confined in Nuclepore and microchannel plates.[8–10] Fig. 3 shows the data plotted according to Eq. 1.

The distance L in the scaling variable, is taken to be the pore diameter in the Nuclepore and microchannel plates. We note that although the cross-sectional geometry is different for cylinders and square channels, the surface to volume ratios ($4/diameter$ and $4/L$, respectively) are identical when the smallest confining length in the pores is taken to be the diameter.

For $T > T_\lambda$, the data scale reasonably well, displaying the same power-law behavior over a wide range of the scaling variable. There is some scatter in the amplitude between runs of various sizes. This may be due to inhomogeneities in the diameter of the cylinders. Non-uniformities in the lithographically patterned channels is not an issue, and it remains to be seen whether these channels, with different L's, will give better collapse. The dashed line is a theoretical calculation of the surface specific heat.[11] These data fall below the expected values in contrast to the planar case where agreement is excellent.[3,5]

We attribute the different behavior at large values of the scaling variable for the square channels to the manifestation of the edge specific heat.[3] In this region, the data for the square channels are consistent with a power-law behavior with an exponent of -2ν. This is indicative of an edge specific heat, and has also been observed in the 0D boxes where the total length of edges is on the order of 6 km.[12] Edge contributions do not play a role in the cylindrical geometries.

For $T < T_\lambda$, the data do not collapse well on a universal locus. This is particularly true near the specific heat maximum (the inflection point near $tL^{1/\nu} \approx 12$). Here, the Nuclepore data collapse among themselves, while the 8 μm and 0.26 μm data define separate loci.[10] The present data "cut across" these latter data in the region of the maximum. For large values of $tL^{1/\nu}$ the summary of the all data is consistent with the expected dependence of the surface specific heat. We note, as in 2D, that the theoretical prediction lies below the data.

4. SUMMARY

We have measured the specific heat of helium confined to 1 μm square channels and compared the results of 1D crossover to previous measurements of 0D, and 2D crossovers. We have also compared these results with measurements in cylindrical geometries to investigate finite-size scaling.

It remains to measure square channels of different sizes to more fully explore scaling behavior.

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