Specific Heat of Helium in 2 μm^3 Boxes, Coupled or Uncoupled?

K.P. Mooney, M.O. Kimball, and F.M. Gasparini

Department of Physics, University at Buffalo, The State University of New York, Buffalo NY 14260, USA

Abstract. We report on recent measurements of the specific heat of helium confined in pill-boxes 2 μm across and 2 μm deep made lithographically on a silicon wafer. The experimental cells distribute liquid from a bulk reservoir to $\sim 10^8$ boxes by an array of very shallow fill-channels (0.019 μm and 0.010 μm) which represent a negligible volume compared to that of the boxes. Since the channels are so shallow, the helium in them becomes superfluid at a much lower temperature than the liquid in the boxes. Therefore, during the course of the heat capacity measurements, the liquid in the channels in always normal, and the cell would be expected to behave as a system of uncoupled boxes. We compare these measurements with one previously made of a cell where the confinement was to 1 μm boxes with an equivalent fill arrangement. While the shift in the position of the specific heat maximum relative to the 1 μm cell is what one would expect on the basis of finite-size scaling, there are discrepancies in the specific heat amplitude between the 2 μm cell utilizing different depth fill-channels, and with the 1 μm cell. It is possible that the channels, even though normal and of negligible volume, provide a weak coupling between the boxes leading to a collective rather than single-box behavior.

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The specific heat of confined ^{4}He near the superfluid transition deviates substantially from bulk behavior as the correlation length ξ grows to be comparable to the the smallest confining spatial length scale L. This has been the subject of both experimental and theoretical work for some time [1].

Using a technique involving photolithography and direct silicon wafer bonding, we have been able to construct experimental cells to enclose helium in a specific geometry. Previously, we have used this method to build cells confining the helium to thin films or long narrow channels of square cross section. Details of cell construction, diagnostics, and mounting procedures can be found in prior publications [2, 3]. Our current cells make use of box-like structures to confine the helium in all three dimensions. Therefore, as the transition is approached, the behavior of the helium crosses over from three dimensional behavior (3D) to zero dimensional (0D).

Measurements where the liquid was confined to boxes of 1 μm have previously been reported [4]. We have constructed two new cells where the box size was 2 μm to investigate finite-size scaling for 0D crossover.

Each cell has on the order of 10^8 boxes. One needs a method of delivering helium from the fill line above the cell to each of the boxes. This is accomplished by patterning the top wafer with very shallow filling channels, 0.019μm in the case of both the 1 μm and first 2 μm cells, and 0.010μm in the case of the second 2 μm cell.

The shallowness of the channels serves two purposes. First, it minimizes the volume of helium contained in the channels compared to that in the boxes. In the case of the

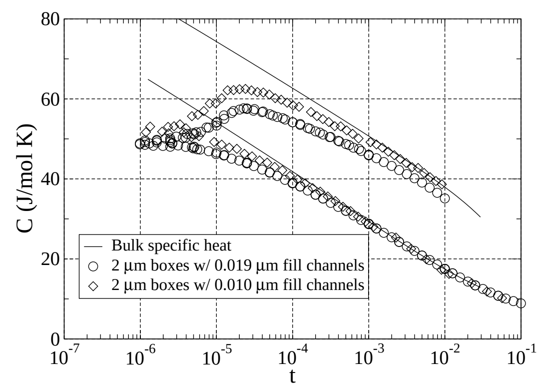

FIGURE 1. Specific heat of helium confined in boxes 2 μm in size but with different sized feed channels. The upper branch is for temperatures less than the bulk T_λ while lower branch is for data with $T > T_\lambda$. The solid lines is the specific heat of bulk helium.

1 μm cell, it represents about 1.8% of the total cell volume. The magnitude of the signal from this contribution is also drastically reduced due to finite-size effects. This minimizes unwanted heat capacity signal from the liquid in the channels. The superfluid transition temperature of the liquid in the channels is at a much colder temperature than the bulk T_λ. At all points during the measurements, the helium contained in the channels is *normal*. We can make a conservative estimate of the transition tempera-

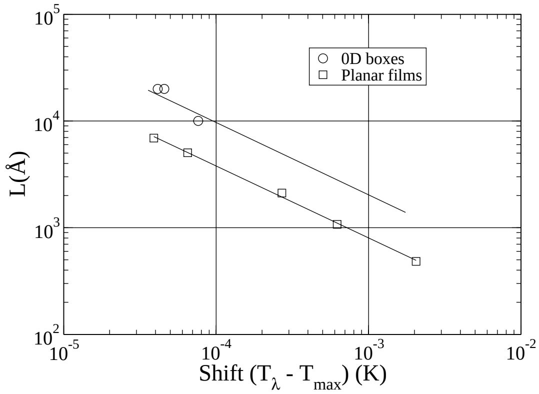

FIGURE 2. Confinement size in angstroms plotted as a function of the shift of C_m for both planar films and boxes.

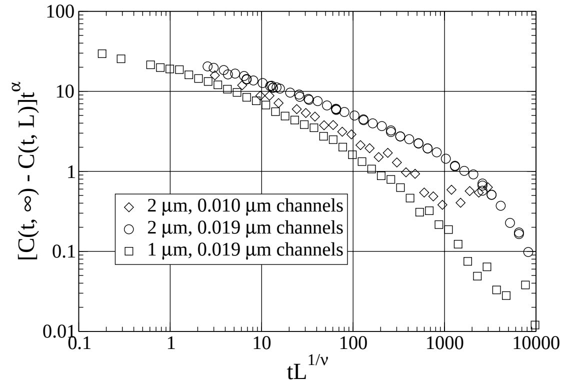

FIGURE 3. Data for both 2 μm cells and the 1 μm cell plotted according to Eq. 1. This is for $T > T_\lambda$ with L expressed in angstroms in the scaling variable.

ture in the channels by approximating the geometry as a 2-dimensional film of the same thickness, and taking the onset of superfluidity to be at the temperature of C_m, the maximum of the specific heat in the channels. We denote this temperature as T_m, and define a corresponding reduced temperature $t_m = (T_\lambda - T_m)/T_\lambda$. Using the data in Ref. [3] and the relation $t_m = a_0 L^{(-1/\nu)}$, gives roughly 10^{-2} for 100 Å thick films. Direct measurements of the superfluid fraction in the channels shows an onset in the vicinity of $t = 2 \times 10^{-2}$. It is desirable to have the superfluid transition colder than the temperature range at which one takes specific heat data so as to ensure the boxes are not coupled via a superfluid link.

Specific heat measurements are done using an AC calorimetry technique. An AC voltage is applied to a thin film heater evaporated onto the bottom of the cell, and the resulting temperature oscillations are detected by one of two germanium thermometers. The magnitude of the oscillations is inversely proportional to the heat capacity.

Figure 1 shows the specific heat for two different cells both patterned with 2 μm boxes. The most striking feature is that the data for the cell with 0.019 μm deep fill channels lies substantially below the data for the cell with the shallower channels. It also begins to deviate from the bulk at a warmer temperature, and never merges back into the bulk at colder temperatures.

The position of the specific heat maximum is the same for both cells. The difference in the position of the maximum between these cells, and the previous 1 μm cell is reasonably consistent with what one would expect on the basis of finite-size scaling. A plot of the confinement size versus the temperature shift in C_m should give a straight line on a log-log plot. This has been done for data taken where the helium was confined to a thin film. We would expect the data for the boxes to define a straight line parallel to the data for the films. While more points are clearly needed in the case of the boxes, the existing data is reasonably consistent with expectations.

On the basis of finite-size scaling, we should be able to cast the data in scaling form:

$$[C(t,\infty) - C(t,L)]t^\alpha = g_2(tL^{1/\nu}), \qquad (1)$$

where ν and α are respectively the correlation length and specific heat exponents, and g_2 is a universal function. Clearly the data plotted in Fig. 1 will not scale since the confinement size is the same while the specific heat is different. When these two data sets are plotted along with data for the 1 μm cell, it is clear that none of these data scale at all. This contrasts markedly with data for the thin films of Ref. [3] which scale very well over many decades of reduced temperature.

It may be that our assumption of isolated boxes is incorrect, and there is some coupling, perhaps via fluctuations, between them. Future work needs to investigate this possibility, and will involve measurements where the size of the fill-channels distance are varied in a systematic way.

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