^{4}He confined to $1\mu m^3$ boxes, 0D crossover, surface and edge effects.

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Abstract

We report measurements of the specific heat near the superfluid transition of ^{4}He confined to $1\mu m^3$ cylindrical boxes patterned in SiO_2. This system crosses from a 3D behavior to a 0D behavior near the transition. This has a marked effect on the specific heat as seen by a pronounced rounding of the maximum and a shift to a temperature much lower than the transition of the bulk system (and systems with 2D or 1D crossover). We plot the data according to correlation-length scaling theory and compare this to a planar system with the same smallest confinement. Compared to our previous studies of planar systems, the 0D cell has 3× the surface to volume ratio as well as ∼750× as much edge length. We examine the regions where surface and edge effect contributions can be separated. We find that the data do not reach the expected value for the surface region. There is also evidence for a region where the term associated with edge contributions dominates.

Key words: Helium four; 0D crossover; Surface specific heat; Correlation-length scaling

Helium confined to uniform small dimensions has been the subject of fundamental research for over three decades. Scaling theories have been proposed[1,2] and experimental tests of these theories[3–5] have been done. We have developed techniques to confine helium to simple geometries with well defined lengths. This allows us to measure a system where *confinement* modifies its behavior while other effects such as *disorder* are not included.

Our latest confinement cell incorporates $\sim 10^9$ cylindrical boxes whose diameter and height are $1\mu m$. Details of a similar cell construction have been given elsewhere[6]. The cell is a two inch diameter silicon wafer that has a layer of silicon dioxide grown on it. Part of this dioxide is then selectively removed, leaving behind open cylindrical boxes with the desired height and width. To complete the cell, a second silicon wafer is directly bonded to the first. This wafer has shallow fill channels (18.5 nm in height and 1 μm in width) patterned onto it. These channels run the length of the cell and connect all the boxes to the helium fill line.

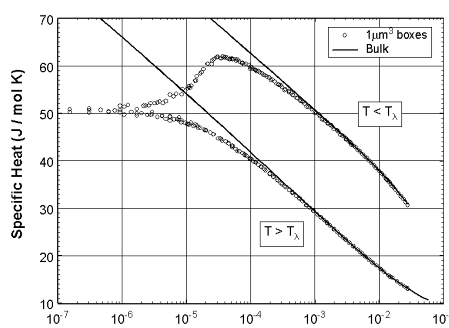

Fig. 1. 0D heat capacity compared to the bulk data. The lines represent the bulk date and the open symbols are the confined system.

To measure the heat capacity, we use a modified AC technique[3,7] where an AC voltage is applied to the heater evaporated on the cell bottom and the temperature oscillations of the helium are read by a thermometer on the top. This allows us to measure the very small samples in our cells, $\cong 30$ μmole.

Figure 1 shows the heat capacity of the helium con-

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fined to the boxes and contrasts it to the unconfined system, the solid lines. The variable t is the reduced temperature t=|1 - T/T_λ|, where T is the temperature and T_λ is the transition temperature of the bulk system. The lower branch is data taken above T_λ and the upper branch is taken below. Notice at large values of t, the data match the bulk data. As one moves closer to the bulk transition, the confined system's heat capacity begins to systematically deviate from the bulk data. This is predicted by finite-size scaling theory.

To transform the data into a predicted scaling form, one uses equation 1.

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

The exponents α and ν are the same as the critical exponents used to describe the bulk heat capacity and correlation length ξ, respectively. L is the smallest spatial length of the confined system. The data above the bulk transition temperature, scaled this way, may be seen in figure 2.

One may write, for temperatures where $\xi \ll$ L, the free energy of the confined system in terms associated with different geometric factors[8]. This is seen in equation 2 with contributions to the free energy from the bulk, surfaces, edges, and corners of each individual confinement box respectively.

$$f \cong f^{(b)}(t) + \frac{1}{L} f^{(s)}(t) + \frac{1}{L^2} f^{(e)}(t) + \frac{1}{L^3} f^{(c)}(t) \tag{2}$$

It is believed that each one of these geometric terms contribute in a limited region of the scaling variable. Therefore, one would have a dominating behavior yielding to another as you move from large values of the scaling variable to smaller ones. The surface, edge, and corner contributions depend on the shape of the confinement only through the amplitude thus the surface term should behave as $t^{-(\alpha+\nu)}$ and the edge term as $t^{-(\alpha+2\nu)}$ in order to agree with the scaling form, Eq.1. The amplitude of the surface term has been calculated by Schloms and Dohm[9] and fits data taken for two dimensional (2D) confinement very well[4]. If one compares the ratio of the surface to volume for the 2D and 0D confinements, one finds this ratio three times larger for the 0D cell. Thus, all one does to adjust the calculated magnitude for the 2D system to the 0D, is to increase the magnitude of the predicted amplitude by a factor of three. This is shown in figure 2 as the dotted line. Unlike the data for the 2D confinement where there is excellent agreement (not shown), these data do not have the proper magnitude and there is no identifiable region where the surface exponent is prominent. The solid line is drawn to have the expected exponent of 2ν for the *edge* contributions to the free energy. The magnitude of this line is adjusted to match the data and the exponent fits rather well. As one proceeds to smaller values of the scaling variable, Eq. 2 gives way to Eq. 1. No comparison with a theoretical f_2 (see Eq. 1) can be made at this time.

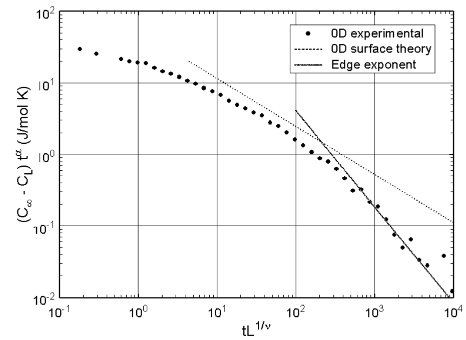

Fig. 2. 0D data scaled according to Eq. 1. The behavior expected from surface effects is given by the dotted line; and, the exponent related to edge effects is the solid line.

In summary, we have presented the first ever measurement for the heat capacity near T_λ with 0D crossover and identify for the first time an *edge contribution* as the first leading deviation from bulk behavior. The overall behavior of these data both above and below T_λ will determine the scaling function f_2 for 0D crossover.

Acknowledgements

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