Heat capacity of mixtures of ^{3}He-^{4}He confined to coupled 1μm boxes.

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Abstract

We have measured the heat capacity of helium mixtures confined to lithographically created cylindrical boxes whose height, 1.08μm, equals their diameter. The specific heat at constant concentration x, C_{px}, is renormalized due to the ^{3}He impurity. Thus, in order to observe critical behavior, a conversion must be made to a specific heat at constant ϕ=μ_3-μ_4, $C_{p\phi}$. The confined system's specific heat, near it's maximum, has values which rise above the bulk system's specific heat at the same temperature. This is unexpected and is true for both $C_{px}$and $C_{p\phi}$. This enhancement, not observed with pure ^{4}He, becomes more dramatic as x and the correlation length increase. The shift of the maximum with x is much larger for the boxes than for 2D confined mixtures. These observations might be related to a "band structure" effect associated with the 18.5 nm channels which connect the cylinders.

Key words: Helium mixtures; 0D crossover; Heat capacity;

^{4}He has been used extensively to study the response of a system to confinement in one or more dimensions. Finite-size effects are manifest when the correlation length, ξ, becomes comparable to the smallest spatial length imposed by the confinement[1]. These effects are believed to obey scaling laws and much effort has been done to verify this[2–4].

If one adds ^{3}He to ^{4}He, the resulting mixture is thought to behave qualitatively the same as the pure system only with an increased correlation length at any given temperature. ^{3}He acts as an impurity which is free to move about in the system. Thus, the movement of ^{3}He *renormalizes* the thermodynamic response and a conversion to a specific heat at constant chemical potential difference between ^{3}He and ^{4}He is required to attempt to scale the data[5,6]. A summary of this conversion can be found in Ref. [7].

Figure 1 shows a scanning electron microscope picture of the confining structure. These are cylindrical boxes 1μm × 1μm in height and diameter. There are about 10^9 of these patterned on a 2 inch silicon wafer. What is not shown in Fig. 1 is the 18.5nm fill channels

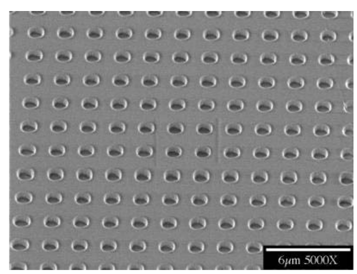

Fig. 1. SEM picture of the 1μm cylindrical boxes.

patterned on a second wafer which is then bonded to the first to construct a cell. Details of the cell construction are found elsewhere[2,8].

Figure 2 shows $C_{p\phi}$ of the confined mixtures. The variable θ is the reduced temperature (distance in temperature from the bulk transition temperature) appropriate to this specific heat. The specific heat of two mixtures, 10.5% and 28.6%, are plotted along with the bulk specific heat of each mixture. At x=0.105, the specific heat exceeds the corresponding bulk value by a slight amount. It also has a somewhat sharper rise to its maximum when compared to pure ^{4}He in the same geometry[9]. The higher concentration however shows a

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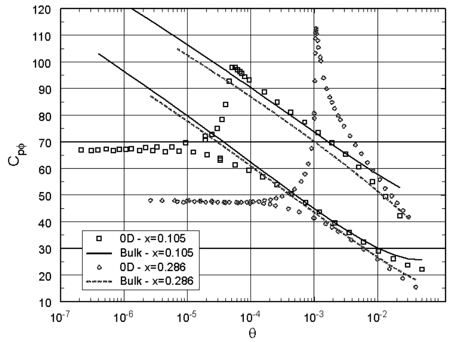

Fig. 2. Plot of the specific heat of helium confined to the 0D boxes once it has been converted from the measured C_{px} to the critical $C_{p\phi}$. Two mixtures are plotted (open symbols) along with the bulk $C_{p\phi}$ for each mixture (solid and dashed lines).

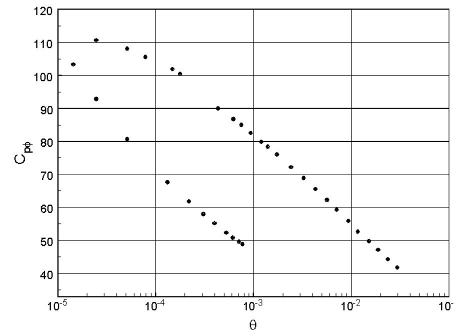

Fig. 3. Plot of $C_{p\phi}$ near the maximum region taking the maximum point as $\theta = 0$. This demonstrates how sharply $C_{p\phi}$ is peaked.

very rapid rise in the specific heat which grows well beyond the bulk system's value at this temperature. *This is totally unexpected*, and was not seen in mixtures confined to a film geometry with spacing L=1μm[7]. Perhaps the magnitude is not the problem (the maximum value is nearly what we measured for the planar confinement) but the position at which this peak occurs. The position is shifted substantially colder relative to the planar geometry. Since the bulk specific heat decreases nearly logarithmically as one moves away from the transition temperature, the maximum for the confined system occurs at a point where the bulk specific heat is lower relative to the 2D peak position. If one examines the 28.6% data, this peak resembles the divergence of the bulk liquid and led us to try to plot it using the temperature of the peak as $\theta =$ zero. This is seen in Fig. 3, with the lower branch having temperatures warmer than the maximum and the upper having temperatures colder than this. Indeed, the two nearly parallel lines indicate just how sharp the peak is.

One possible explanation of this anomalous specific heat is the coupling of boxes via the shallow fill channels. We have measured the superfluid density in these channels[9] using a technique developed in our lab know as adiabatic fountain resonance (AFR). Details of this technique can be found elsewhere[10]. From this, we know the helium in the boxes is superfluid *before* the fill channels approach their transition temperature. Once the channels become superfluid, we have the situation where we have two "bulk" superfluid reservoirs connected by a shallow channel. This coupling, which increases as x (and hence ξ) increases, seems to encourage fluctuations at a temperature where they are normally quenched in the bulk system.

In summary, we have measured mixtures of helium confined to 1μm^3 boxes connected by shallow fill channels. The specific heat of this system is very different from a planar confinement which has the same smallest spatial length. We believe this is mainly due to the increased correlation length of the mixtures coupling together boxes through the shallow fill channels. Much theoretical and experimental work needs to be done to verify this picture.

Acknowledgements

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