Vortex core size in $^3$He-$^4$He films with monolayer superfluid $^4$He

Han-Ching Chu, Gary A. Williams
Department of Physics and Astronomy, University of California, Los Angeles, CA 90095, USA

Abstract
The superfluid transition of $^3$He-$^4$He mixture films adsorbed on alumina powder is studied, with a $^4$He superfluid coverage near one layer. With up to 1.3 layers of $^3$He added, the transition becomes strongly broadened, indicating a linear increase in the vortex core size for $^3$He coverages below one layer. Annealing of the sample mixture at 4.2 K is found to be critically important in ensuring a homogeneous film across the porous substrate.

Keywords: $^3$He-$^4$He mixture films; superfluid transition; vortex core size

Studies of the superfluid phase transition of helium films adsorbed in porous materials provide the only technique known for measuring the vortex core size in films [1,2]. At length scales smaller than the pore size of the material the film is two-dimensional, whereas at larger scales the film is multiply connected and becomes three-dimensional [3]. The broadening of the transition in the 2D to 3D crossover region is essentially that of a finite-size Kosterlitz-Thouless (KT) transition [4–6], and depends on the ratio of the pore size to the vortex core size. For a fixed pore size the degree of the transition broadening allows the core size to be studied as a function of film thickness and $^3$He coverage [2].

We report here measurements on films with a $^4$He superfluid coverage (at $T = 0$) of $d_4 = 0.95$ layers, higher than in our earlier studies using submonolayer coverages [1,2]. The same torsion oscillator technique and slip-cast alumina powder substrate are employed as in the previous measurements. The pore size of the substrate is estimated [7] to be about 100 Å, smaller than the nominal powder diameter of 500 Å because the strong surface tension forces in the slip-casting process [1] efficiently pack the smaller powder grains into the spaces around the larger ones.

Figure 1 shows the measured oscillator period shift of the pure $^4$He film, and the same film for increasing coverages of $^3$He. As discussed in Refs. 1 and 2 these are easily calibrated in terms of the areal superfluid density, and as found before the transitions scale with the universal KT line, but are broadened above it as the transition crosses over to 3D. The increasing broadening of the transition as $^3$He is added is readily evident in the figure.

Fitting the data to the finite-size KT model used in the earlier work [1,2] yields the vortex core radii shown in Fig. 2. The present results are the solid circles, while the open circles are the previous results [2] for a film with a thinner $^4$He coverage, $d_4$...
= 0.55 layers. Both show a linear increase in the core size with $^3$He, but with a lower slope for the monolayer $^4$He film. There appears to be a leveling of the increase in the core size for $^3$He coverages above one layer, as might be expected since any further $^3$He will sit well above the $^4$He layer and only weakly interact with it. This is also consistent with the reduced suppression of the superfluid density in Fig. 1 for the curve with 1.3 layers of $^3$He, compared to the changes in the films with 0.7 and 1.0 layers. Further measurements currently in progress with higher $^3$He coverages appear to show little further change in the core size (to be reported elsewhere [2]).

We see no evidence in this data of any lateral puddling or phase separation of the $^3$He. We also do not find any evidence of a "second transition" observed in other studies [8]. On warming the mixture films to well above $T_c$ the only observable change in the period shift is that above about 0.8 K a slight increase in the period shift is seen due to evaporation of $^3$He from the film into the vapor.

After each increment of $^3$He was added to the $^4$He film, the cryostat was warmed to 4.2 K and left there for more than 24 hours to anneal the $^3$He and ensure that it is uniformly distributed across the substrate. We have found that this is a critically important step for obtaining reliable data. On one run we added 0.4 layers of $^3$He to the $^4$He film, and omitted the annealing step. At higher temperatures the data were similar to the 0.4 layer data of Fig.1 (shifted up in temperature by about 30 mK), but below 0.2 K there was a very abrupt and very large increase in the period shift that even exceeded the period shift of the pure $^4$He film. It is clear that the $^3$He was nonuniformly distributed in the oscillator; any measurements made in the past with mixture films in porous materials that did not include an annealing step probably cannot be regarded as reliable.

This work is supported by the U. S. National Science Foundation, DMR 97-31523.

References

[1] H. Cho, G. A. Williams, Phys. Rev. Lett. 75 (1995) 1562.
[2] H. Cho, G. A. Williams, J. Low Temp. Phys. 110 (1998) 533 ; H. Cho, H. Chu, and G. A. Williams, to be published.
[3] G. Csathy, D. Tulimieri, J. Yoon, M. Chan, Phys. Rev. Lett. 80 (1998) 4482.
[4] V. Kotsubo, G.A. Williams, Phys. Rev. B 33 (1986) 6106.
[5] F. Gallet, G.A. Williams, Phys. Rev. B 39 (1989) 4673.
[6] K. Shirahama et al., Phys. Rev. Lett. 64 (1990) 1541.
[7] N. Mulders, J. Beamish, Physica B 165 & 166 (1990) 573.
[8] X. Wang, F. Gasparini, Phys. Rev. B 38 (1988) 11245.