Superfluid Phase Transition of ^{3}He-^{4}He Mixture Films Adsorbed on Alumina Powder

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The superfluid phase transition of ^{3}He-^{4}He mixture films adsorbed on 500 Å alumina powder has been studied for mixture films whose superfluid thickness is less than a monolayer. The transitions are found to be controlled by the Kosterlitz-Thouless critical line, but a strong broadening of the transition is observed as the ^{3}He concentration is increased. Analyzing the broadening in terms of a KT vortex-pair theory modified for the the finite powder size yields a vortex core parameter which increases nearly linearly with added ^{3}He. Also observed in these measurements is a temperature-dependent and ^{3}He-dependent depletion of the superfluid density at low temperatures, which is thought to arise from the high-frequency ripplon/third sound excitations of the film.

In previous work we have studied the superfluid phase transition of ^{4}He films adsorbed on 500 Å slip-cast alumina powder.[1] As the superfluid thickness was reduced below a monolayer the width of the phase transition was found to broaden considerably. This is readily explained in the context of models of the Kosterlitz-Thouless (KT) transition in porous materials.[2–4] The finite grain size of the porous material imposes a cutoff length scale R at which there is a 2D to 3D crossover, and this results in a broadening of the transition which depends on the ratio R/a_o, where a_o is the core radius of the KT vortex pairs. In the submonolayer superfluid films the core size must increase as the macroscopic wavefunction becomes more and more dilute, giving rise to the increased broadening that was observed.

We have now extended these measurements to ^{3}He-^{4}He mixture films

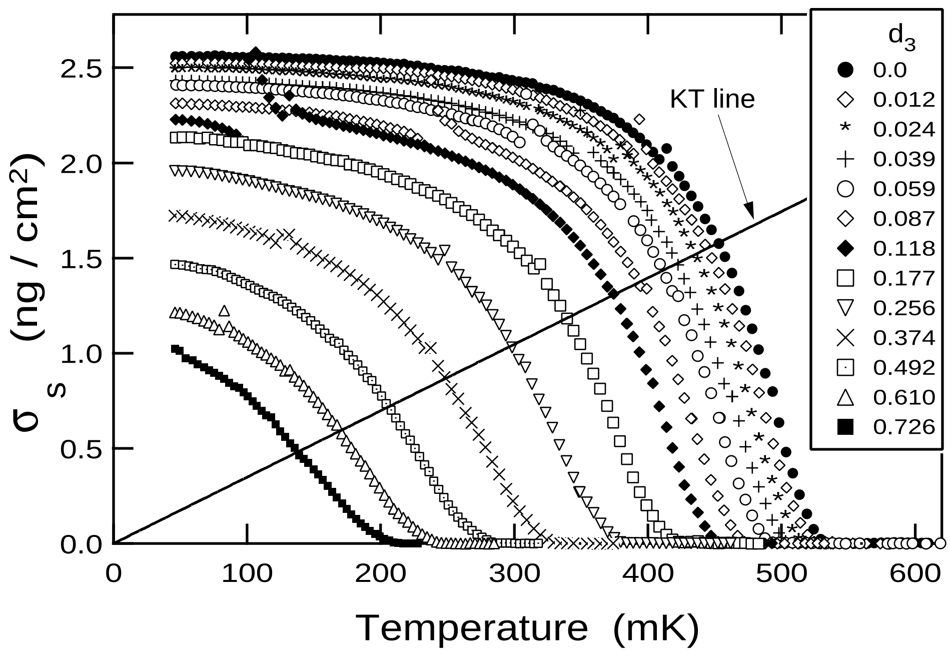

Fig. 1. Areal superfluid density versus temperature for films with increasing ^{3}He concentration.

over a wide range of ^{3}He and ^{4}He concentrations. The addition of ^{3}He is found to strongly broaden the phase transition, indicating that the ^{3}He acts to further increase the vortex core size. This is not surprising, since ^{3}He is well known[5] to increase the core size in bulk superfluid ^{4}He. However, unlike the abrupt condensation of ^{3}He found on the cores in the bulk, we find a gradually increasing core size that is proportional to the amount of ^{3}He added. This may be a consequence of the dilute nature of the submonolayer superfluid films.

The same torsion oscillator cell of Ref. 1 is utilized for these measurements. The only change from the experimental procedures used there is that after each addition of ^{3}He the cell is warmed to 4.2 K for 24 hours to ensure that the ^{3}He is uniformly distributed across the powder. Figure 1 shows the results for the areal superfluid density of a series of films in which ^{3}He is progressively added to a fixed amount of ^{4}He. The starting ^{4}He film has a superfluid thickness of $d_4 = 0.55$ layers, where we define statistical layers using the convention (based on the zero-bar bulk liquid densities) that one layer of ^{4}He corresponds to a coverage of 12.8 μmoles/m^2 and one layer of ^{3}He is 10.7 μmoles/m^2. The data of Fig. 1 clearly shows that the transition scales with the universal KT line as the ^{3}He reduces the $T = 0$ superfluid density, in good agreement with the results for mixture films on

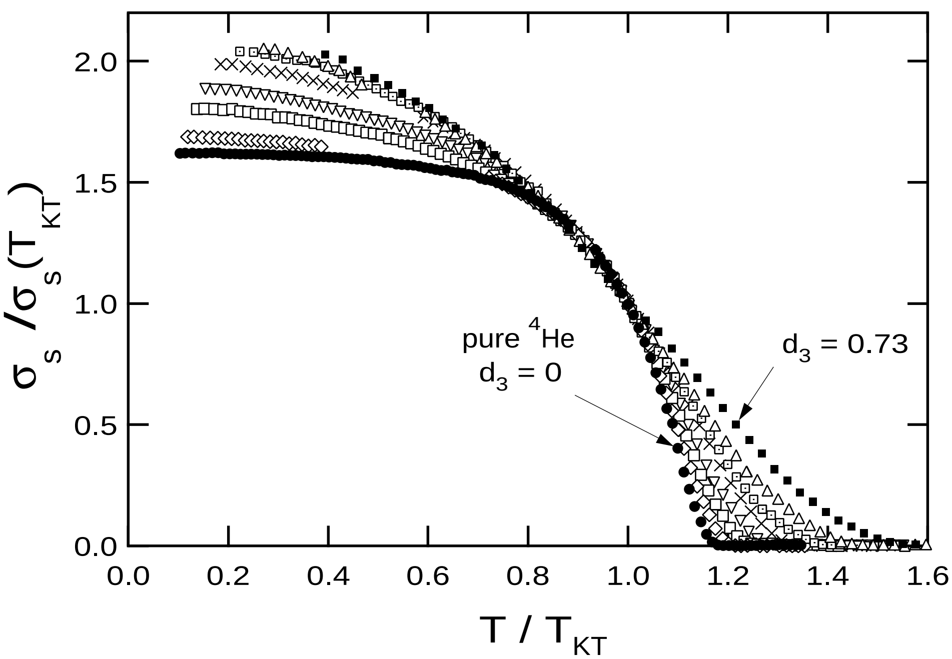

Fig. 2. Normalized superfluid density versus normalized temperature (same symbols as Fig. 1). Only the higher coverages are shown.

a flat substrate.[6] By extrapolating the data to T = 0 we extract a roughly constant ^{3}He effective mass of 1.25 ^{3}He masses, comparable to those found for thicker films.[7] The main difference in Fig. 1 from the the flat-substrate results is in the broadening of the transition; the addition of ^{3}He is seen to further increase the broading of the transition. This is most clearly seen by replotting the different curves normalized by the values T_{KT} and $\sigma_s(T_{KT})$ where they cross the KT line, shown in Fig. 2. In the transition region $T/T_{KT} > 1.0$ there is a continuous broadening as ^{3}He is added.

The data of Fig. 2 is analyzed as described in Ref. 1 to extract values of the core size, shown in Figure 3. The only difference from Ref.1 is that the crossover length scale is now taken to be the pore diameter of 100 Å , which (as discussed at the end of Ref. 1) is probable a better estimate of the length scale where 3D vortex structures begin to play a role. The core size increases linearly with the added ^{3}He coverage, with no sign of any abrupt changes that might signal condensation of ^{3}He at the core.

Figure 4 compares the core size with the pure ^{4}He results of Ref. 1 (reanalyzed to account for the different crossover length and for a slight shift in our temperature scale calibration at high T). Also shown are results from runs where the ^{3}He was kept constant and the ^{4}He coverage was changed.

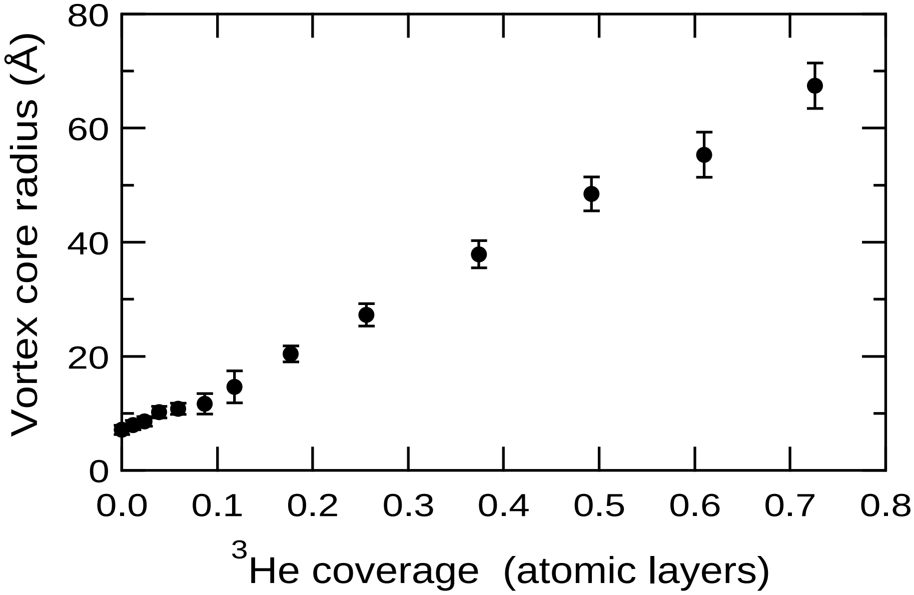

Fig. 3. Core size as a function of ^{3}He coverage for the film with $d_4 = 0.55$.

This data should be useful for comparison with theoretical simulations,[8,9] if those models can be extended to include the case of ^{3}He in low-density superfluid ^{4}He. The preliminary results of simulations of vortex structures in pure ^{4}He films[9] do show a core size increasing as the coverage is lowered, in agreement with the ^{4}He results shown in Fig. 4.

The broadening of the transition that we observe in the mixture films is quite consistent with the early results of Smith *et al.*[10] for films in porous Vycor glass. They found a very strong broadening of the transition when ^{3}He was added to a ^{4}He film with a value of $T_{KT} \approx 75$ mK. This is additional evidence that the superfluid transitions of films on the two substrates are nearly identical.[1]

The small glitches in Fig. 1 are mode-pulling effects due to a third-sound resonance crossing the oscillator frequency, as discussed in Ref. 1. An unusual feature seen in the mixture films is a splitting of the third sound velocity, most easily seen in the double glitch of the $d_3 = 0.118$ curve (and also apparent as a double peak in the oscillator dissipation). The splitting of the third sound velocity is small (< 1 m/s) and can only be resolved when the third sound mode happens to intersect σ_s where it has a small temperature dependence. This splitting may be related to that predicted for suface second sound,[11] although it is unclear that the ^{3}He mobility could be large enough to allow such a mode, where the ^{3}He density oscillates.

The spread of the normalized data in Fig. 2 for $T/T_{KT} < 1.0$ arises from

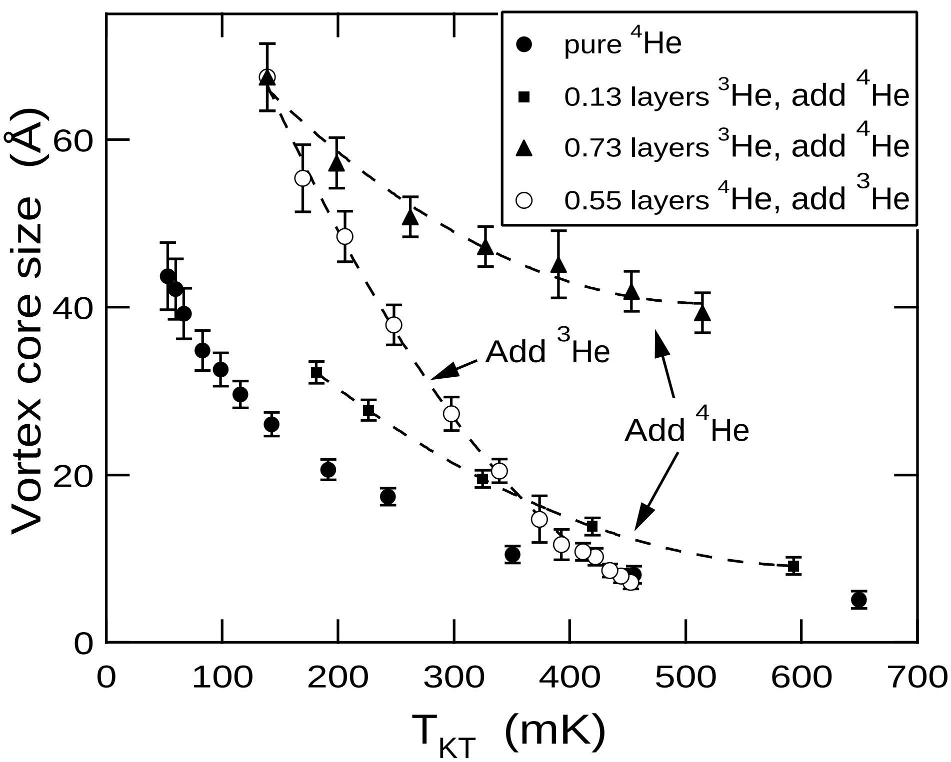

Fig. 4. Core size for different ^{3}He and ^{4}He coverages.

a depletion of σ_s that is observed at low temperatures where vortices are not excited, and which is found to vary as $\sigma_s(\mathrm{T})/\sigma_s(0) = 1 - \beta \mathrm{T}^2$. The values of β are shown in Figure 5 for pure ^{4}He and two mixtures of fixed ^{3}He coverage and varying ^{4}He coverage. It is the rapid increase of β with ^{3}He that leads to the low-temperature variation seen in Fig. 2. It is likely that this normal fluid component arises from thermal third sound/ripplon excitations in the film, which are known from theory[12] to have a linear dispersion relation even at very large wavenumbers. The T^2 dependence would require a 1D excitation, which could well be the case for wavelengths greater than the powder grain size (a wave propagating on a cylindrical rod will be effectively 1D for wavelengths greater than the rod diameter). From Landau theory the coefficient of the T^2 term would be expected to vary as c_3^{-3}, where c_3 is the third sound velocity, and this is at least qualitatively consistent with Fig. 5. Decreasing the film thickness by removing ^{4}He decreases c_3, accounting for the rise in β as d_4 decreases. Adding ^{3}He then further decreases c_3, increasing β even more, as seen in Fig. 5.

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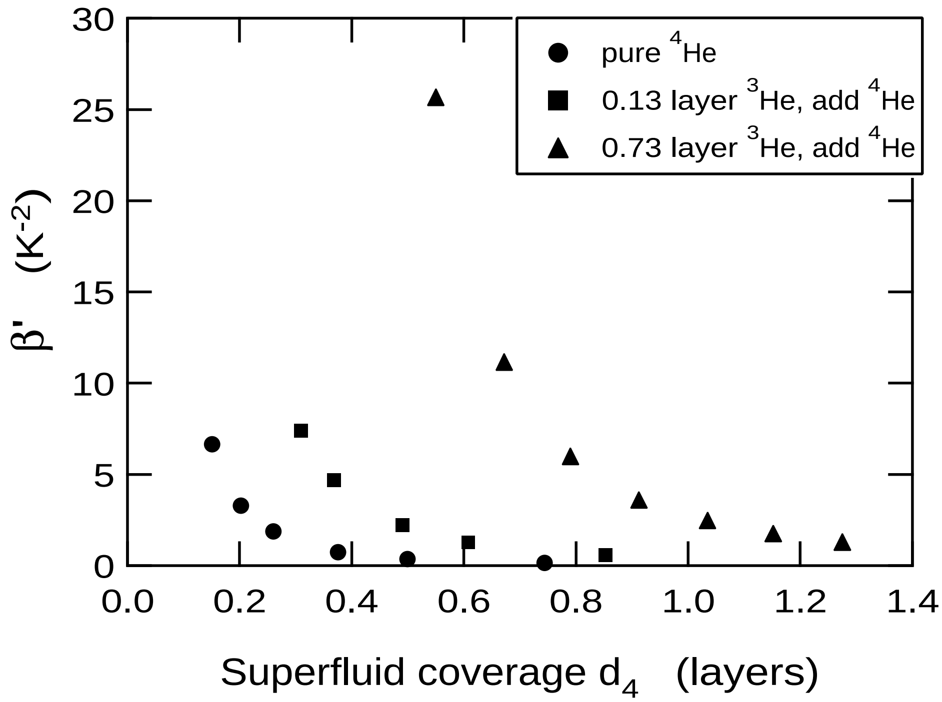

Fig. 5. Coefficient β' of the T^2 depletion of σ_s at low temperatures.

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