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Specific heat of thin ^{3}He films on a disordering substrate

Charles J. Yeager, Lindsay M. Steele,* and Daniele Finotello
Department of Physics, Kent State University, Kent, Ohio 44242

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We report measurements of the specific heat of thin ^{3}He films ranging in coverage from 10 to 35 μmol/m^2 over the temperature regime between 0.1 and 1 K. The films were formed in the 0.2-μm-diameter cylindrical pores of aluminum oxide Anopore membranes. A heat-capacity shoulder centered at a temperature that decreases with increasing thickness is observed. This behavior is similar to that of localized ^{4}He films adsorbed in several heterogeneous substrates. Such a heat capacity signature may be viewed as a universal property of films adsorbed on disordering surfaces; parameters that characterize it are substrate dependent, or nonuniversal. The results are analyzed using existing models for helium films on heterogeneous substrates.

I. INTRODUCTION

There has been considerable interest in the study of thin helium films in the presence of a random potential. For ^{4}He films there is a universal behavior independent of absorbate: superfluidity occurs when the film thickness d (or coverage n) is greater than a critical, substrate-dependent value d_c (n_c), which for most substrates ranges between one and two layers. This is the result of the strong van der Waals attraction between substrate and helium atoms that tightly binds these films to the substrate, so they are often considered inert or localized. The inert layer screens additional atoms from the substrate's potential thus providing a smoother potential for the onset of superfluidity. Studies of ^{4}He films focusing on the crossover from the localized to the superfliud behavior have used strongly disordering, heterogeneous, substrates such as porous Vycor glass and Mylar polyester film. They have raised important questions that have been addressed theoretically[1-5] about the role of disorder on the behavior of localized and superfluid films.

Specific-heat studies of localized ^{4}He films on disordering (noncrystalline) substrates have shown the existence of a "universal" feature: a specific-heat shoulder (or bump) appearing at a temperature that decreases with increasing coverage (thickness). This was seen in films adsorbed in aluminum oxide Anopore membranes,[6] cellulose acetate Millipore fibrous filter paper,[7] and Mylar film.[8,9] The shoulder disappears once the film becomes superfluid at that temperature. While parameters that typify the bump, the area under it, the width, and lowest temperature position, are substrate dependent, there is an overriding similar behavior among the substrates. Specific-heat anomalies, similarly behaving with coverage, were also observed in Vycor[10,11] and Xerogel[12] glasses. This is interesting since eventually the specific heat of superfluid films in these substrates reflects their different dimensionality: two-dimensional (2D) in Anopore, Millipore, or Mylar, while 3D-like in the porous glasses. For localized coverages, the existing similarities suggest a strong disordering influence introduced by the substrate potential on the film's behavior.

Most studies with ^{3}He films have taken place with surfaces introducing little or no disorder: films adsorbed on order exfoliated graphite or Grafoil,[13,14] and on the surface of thick ^{4}He films.[15] Calorimetry measurements for ^{4}He and ^{3}He films on graphite showed the existence of a rich phase diagram reflecting the regular nature of the substrate.[16,17] In particular, the behavior of ^{3}He films on Grafoil changes from an interacting 2D Fermi gas for the lowest coverages to a 2D Debye solid as the thickness increases toward the monolayer completion.[14] Upon monolayer completion, the second layer forms and shows a similar interacting 2D Fermi gas behavior. Studies by Gasparini and co-workers for ^{3}He-^{4}He films in Nuclepore membranes[15,18] indicated that for very thick ^{4}He films the ^{3}He atoms exist preferentially at the surface of the ^{4}He rather than at the underlying substrate, behaving as an ideal 2D Fermi gas with weak interactions. This view is supported by extensive NMR studies by Hallock and collaborators.[19]

Previous work with ^{3}He films on disordering substrates include the pioneering work of Dash and Stewart on argon-coated copper,[20] and that of Brewer and coworkers in Vycor.[21] In the latter, near monolayer films were studied over the temperature range between 1 and 4 K; the specific heat was well described by a quadratic temperature dependence plus a constant term. Films adsorbed on these heterogeneous substrates showed no gas-like phase even for submonolayer coverages as thin as 0.1 helium layer in argon-coated copper.[20]

Here, we present results of a systematic specific-heat study for ^{3}He films ranging from submonolayer to multilayer films, over the temperature range between 0.1 and 1 K. Films were formed inside the 0.2-μm-diameter, nearly cylindrical parallel pores of aluminum oxide Anopore membranes,[6] a substrate previously used in our ^{4}He films[9,22] studies. The motivation for this work stems from the results of the above-mentioned studies for both localized and superfluid films on disordering substrates. In particular, for superfluid ^{4}He films[22] the specific heat showed a round peak that was interpreted in terms of the

Kosterlitz-Thouless (KT) vortex unbinding mechanism.[23] Such a superfluid feature should not exist in the present study.

To highlight the ^{3}He results we find a heat-capacity shoulder centered at a coverage-dependent temperature. Compared to ^{4}He, the shoulder is seen over wider thickness and temperature regimes. The ^{3}He results are analyzed using models for helium films adsorbed on heterogeneous substrates and are compared to those for ^{4}He adsorbed on disordering substrates. They are also contrasted to results in Graphite, Vycor, and for ^{3}He on the surface of thick ^{4}He films. As expected, no evidence of a specific-heat broad and round KT peak exists in ^{3}He films.

II. EXPERIMENTAL DETAILS

The substrate used in these studies is inorganic Anopore membranes. A full description of their properties can be found elsewhere.[24,25] The specific heat was measured using an ac calorimetry technique.[26,27] Here, a sinusoidal voltage applied through a resistive heater attached to the experimental cell at a frequency f induces thermal oscillations in the sample at a frequency $2f$, whose magnitude T_{ac} is inversely proportional to the total heat capacity of the sample. The total measured heat capacity is calculated from

$$C = P_{PP}[32(\sqrt{2})\pi f T_{ac}]^{-1} \ . \tag{1}$$

P_{PP} is the peak-to-peak power dissipated at the heater of resistance **R**.

The experimental cell was the same employed in our ^{4}He studies[9,22] with a total surface area of 4.37 m^2. ^{3}He (99.95% pure) films were adsorbed in the experimental cell, annealed at $T > 4.2$ K overnight, and then slowly cooled to the lowest temperature of 0.1 K. Data were taken at different heating powers, frequencies, heating and cooling, and increasing and decreasing the film thickness. Although we studied as many as 20 ^{3}He films from 10 to 60 μmol/m^2, here, we restrict ourselves to coverages up to 35 μmol/m^2.

III. RESULTS AND DISCUSSION

Given the heterogeneous nature of substrate, films are labeled in terms of the coverage in μmol/m^2. From nitrogen adsorption isotherms and the ratio of nitrogen to helium areal densities the monolayer completion is estimated to be 18.3 μmol/m^2. If coverages greater than a monolayer are considered liquid with a bulklike density of 0.07 g/cm^3, then one liquid layer corresponds to 8.40 μmol/m^2 as compared to 12.82 μmol/m^2 for ^{4}He.

The heat capacity for the empty cell and three thinnest films studied is shown in Fig. 1. The 10 μmol/m^2 film is dominated by the heat capacity of the empty cell and does not deviate significantly over the temperature range of the measurement. With increasing thickness, the deviation from the addendum occurs at lower temperatures and a shoulder emerges. For higher coverages, the temperature position of the center of the shoulder shifts to lower temperatures.

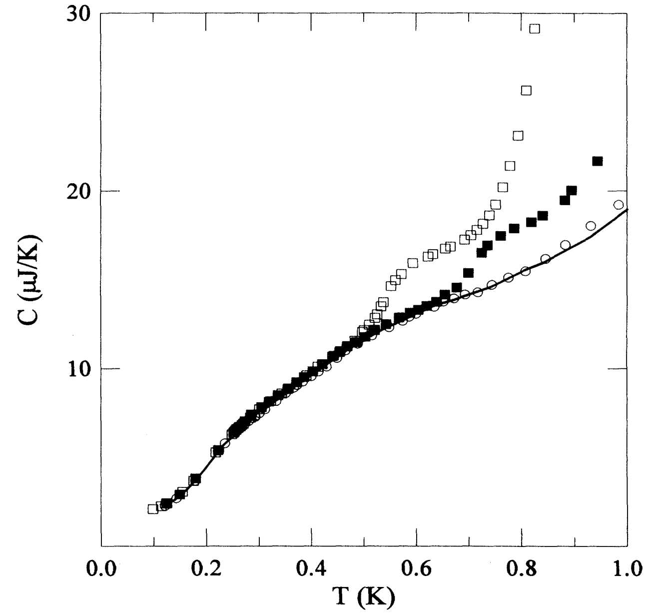

FIG. 1. Heat capacity as a function of temperature for the empty cell (solid line) and three ^{3}He films in Anopore. Coverages, in μmol/m^2, are 10.5 (○), 15.04 (■), and 17.04 (□).

The evolution of the shoulder (bump) towards low temperatures is best illustrated in Fig. 2, where we plot the specific heat for eight films spanning a wide coverage range. The addendum heat capacity of the cell was fitted to a polynomial in temperature and subtracted from these data. The bump is centered at 0.75 K for the 15.04 μmol/m^2 film decreasing to 0.1 K for the 35.05 μmol/m^2 coverage. Results for the three thicker coverages are expanded in the inset to emphasize the narrowing of the bump. As quantified by its temperature width ΔT, the bump sharpens considerably decreasing from 205 to 77 mK. The area under the bump above an arbitrarily chosen linear background decreases from 1.75 to 0.26 mJ/mol with coverage. The magnitude of the specific heat at the midpoint of the bump is essentially coverage independent. The coverage dependence of the area, width, and the specific-heat maximum are explicitly shown in Fig. 3, and listed in Table I. These parameters are all well fit by simple linear expressions:

$$A(\mathrm{mJ/mol}) = -0.066n + 2.587 \ , \tag{2}$$

$$\Delta T(\mathrm{mK}) = -0.0073n + 0.302 \ , \tag{3}$$

$$C_B(\mathrm{mJ/mol\,K}) = 0.636n + 28.396 \ . \tag{4}$$

Specific-heat bumps with a similar coverage dependence were also observed in our studies with ^{4}He films in Anopore, Millipore, and Mylar.[9] As a consequence of their superfluid behavior, the ^{4}He bumps reached a coverage where they disappeared giving way to a small specific-heat peak that grew in magnitude while shifting to higher temperature as the coverage was continuously increased.[9,22] The round and broad ^{4}He specific-heat

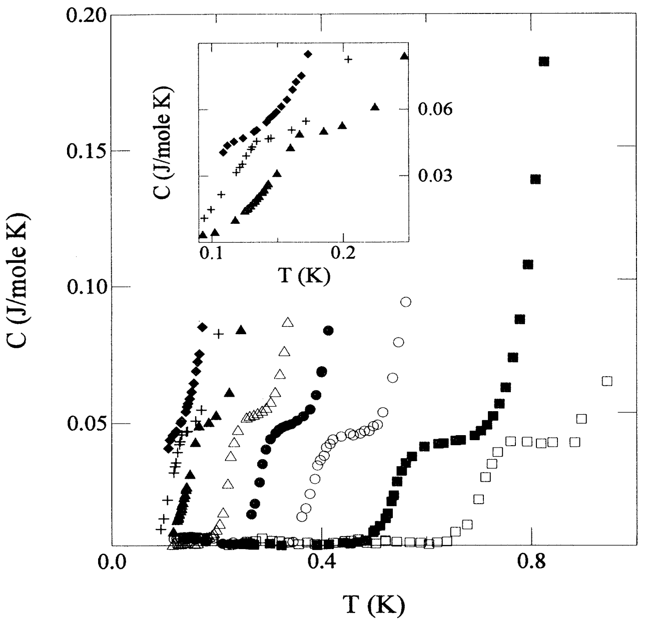

FIG. 2. Specific heat as a function of temperature for eight ^{3}He films after empty cell subtraction. Coverages shown are 15.04 (□), 17.04 (■), 20.54 (○), 23.41 (●), 25.92 (△), 30.05 (▲), 32.55 (+) and 35.05 (◆) μmol/m^2. Note the bump position shifting to lower temperature as the coverage increases. The inset shows the three thickest films on an expanded scale.

peak was interpreted in terms of the 2D Kosterlitz-Thouless vortex unbinding mechanism.[22] Since ^{3}He films are not superfluid at these temperatures, as evidenced by the results shown in Figs. 1 and 2, no peak is present. In addition, combining the ^{3}He and ^{4}He results indicate that the shoulder arises from the interaction between normal ^{3}He (or ^{4}He) and the underlying substrate.

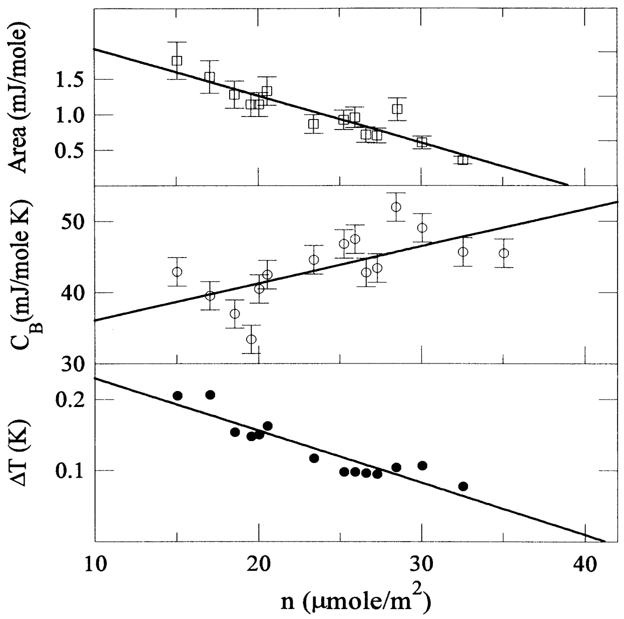

FIG. 3. Coverage dependence of area under the bump (□), specific-heat magnitude at the middle of the bump (○), and temperature width (●). Linear fits to the data are indicated by solid lines. Unless shown error bars are of the size of the symbols.

It is important to contrast the Anopore films results. First, while the temperature width, ΔT, of the ^{4}He bump decreases from 365 to 200 mK for coverages from 15.4 to 24.4 μmol/m^2,[9] the specific-heat magnitude at the middle of the bump increases in such a manner that the area un-

TABLE I. Summary of the bump characteristic for ^{3}He and ^{4}He films in Anopore and ^{4}He films in Millipore: The temperature (T_b) position and specific-heat (C_b) magnitude at the center of the bump, the temperature width (ΔT) of the bump, and the area of the bump, and gap energy (Δ/k_B) fit parameter from Eq. (5). The uncertainties for both area of the bump and Δ/k_B are 20%.

	Coverage (μmol/m^2)	T_B (mK)	C_B (mJ/mol K)	ΔT (mK)	Area (mJ/mol)	Δ/k_B (K)
^{3}He in Anopore	15.04	753	43	205	1.76	16.4
	17.04	585	40	206	1.53	10.9
	20.54	416	43	162	1.20	5.5
	23.41	302	45	117	0.87	2.9
	25.92	240	48	98	0.24	3.7
	30.05	167	49	107	0.12	0.6
	32.55	134	46	77	0.13	0.5
	35.05	117	46	NA	NA	NA
^{4}He in Anopore	17.09	923	94	315	4.52	10.7
	19.18	772	79	250	3.64	10.4
	22.06	645	89	214	3.73	8.7
	24.40	608	112	202	4.09	8.5
^{4}He in Millipore	17.58	789	56	237	3.11	15.5
	19.58	702	50	245	2.68	11.8
	22.58	592	52	196	2.32	10.6
	24.27	552	64	169	2.76	9.0

der the bump remains constant at ~4.2 mJ/mol, the values of the area under the bump in Millipore and Mylar are also constant of magnitude 2.7 and 9.0 mJ/mol respectively. In all instances these are larger than for the ^{3}He films where the area decreases linearly from 1.75 to 0.26 mJ/mol over the same range of thicknesses (see Table I). A second method to compare both sets of results is to treat ^{3}He and ^{4}He in terms of equivalent layers. Assuming an identical solid layer of 18.3 μmol/m^2 and liquid overlayer of 8.4 μmol/m^2 for ^{3}He and 12.8 μmol/m^2 for ^{4}He, the ^{3}He bump is seen from 0.8 layers to nearly 3 layers while the ^{4}He bump is seen from 0.8 to 1.5 layers a consequence of the eventual superfluid behavior of the latter. Thus, over the same thickness change, 0.8–1.5 layers, the ^{3}He bump area is constant (to within 20%) as in the ^{4}He case.

The magnitude of the specific heat at the center of the ^{3}He bump is a factor of 2 smaller than for ^{4}He. For the same coverage, the ^{3}He bump appears at a lower temperature (0.3–0.4 K) than the corresponding ^{4}He bump; the magnitude of the specific heat of ^{3}He films is larger than that of an equivalently thick ^{4}He film. This is as in bulk where, for $T < 1$ K, the ^{3}He specific heat is almost 2 orders of magnitude larger than for ^{4}He. For films, although the van der Waals attraction to the substrate does not distinguish between isotopes, the ^{3}He has a larger zero point motion.

An additional feature is also present at higher temperatures for ^{3}He films in Anopore: a distinct break in the specific-heat temperature dependence; below the break the specific heat decreases sharply with temperature. The break temperature also decreases with increasing thickness; it is at 0.76 K for the 19.55 μmol/m^2 film, shifting to 0.22 K for the 50.05 μmol/m^2 film. A few films exhibiting this break are shown in Fig. 4 where we plot the specific heat divided by temperature as a function of temperature. A high-temperature break with a similar temperature dependence was observed in superfluid ^{4}He films in Anopore;[9] for equivalent coverages it appears at a lower temperature for ^{3}He. Were such a change in temperature dependence associated with desorption, an activation energy plot ($\ln\{CT^3\}$ vs T^{-1}) (Refs. 28 and 29) would show a linear region of slope of $-q_{ST}/k_B$ where q_{ST} is the heat of adsorption. When both the ^{3}He and ^{4}He are analyzed is this manner no well-defined linear regions are found.

Most of the existing work with ^{3}He films has taken place with crystalline graphite as the underlying substrate. Thus, to better understand the behavior of films in Anopore and to show that they are a manifestation of substrate-induced disorder, we first review results for ^{3}He films on graphite, and on the surface of ^{4}He films. In graphite, ^{3}He films less than 9.97 μmol/m^2 (0.06 Å^{-2}) had a specific heat of ~1 Boltzmann, k_B, per atom (or 8.3 J/mol K) at temperatures above 2 K,[14] as expected for an ideal 2D gas. As the temperature was lowered, the specific heat decreased monotonically to zero and was modeled as a nonideal 2D quantum gas. For ^{3}He on top of thick ^{4}He films adsorbed in Nuclepore filters, ^{3}He films from 0.3 to 1 layer thick (2.8–10.6 μmol/m^2) resided preferentially on the surface of a 10-Å-thick (~54 μmol/m^2) ^{4}He film.[15] The ^{4}He film offers a homogeneous surface for the ^{3}He atoms screening out the underlying substrate: the ^{3}He essentially behaves as an ideal Fermi gas of quasiparticles. Its heat capacity increased linearly with temperature from 40 to ~150 mK reaching the expected k_B value at higher temperatures.

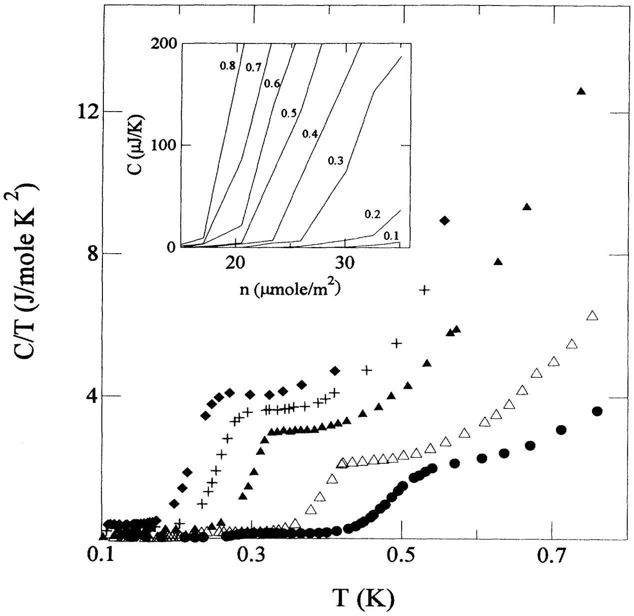

FIG. 4. Specific heat divided by temperature as a function of temperature for the thickest films of Fig. 2 (same symbols). Notice the break in the heat-capacity temperature dependence shifting to lower temperatures with coverage. Inset: heat-capacity isotherms, to indicate the continuous growth with coverage at all temperatures.

If we assume that ^{3}He films on Anopore form an ideal Fermi gas we would expect a linear temperature dependence in the specific heat, rising to 1 k_B per atom as it becomes a classical gas. However, the magnitude of the specific heat for ^{3}He films in Anopore is well below such expectations. The specific heat for an ideal Fermi gas would be 1.4 J/mol K at 0.4 K for a $n = 25.92$ μmol/m^2 film, which is more than an order of magnitude larger than our data. Thus, we cannot associate the specific-heat shoulder in our ^{3}He data with the evolution from a 2D Fermi to a classical gas. ^{3}He films in Anopore behave differently from those in graphite or on top of ^{4}He; the lack of a 2D gas phase agrees with all previous work of films on heterogeneous substrates.

Van Sciver and Vilches' work with ^{3}He on graphite did reveal a heat-capacity feature that might be comparable to the present observations. For submonolayer ^{3}He films, they found a specific-heat shoulder near 0.1 K, a temperature position that was independent of thickness;[14] by comparison to bulk behavior, it was attributed to ^{3}He-^{3}He interactions. In addition, a near monolayer film had properties of a 2D solid: a T^2 specific-heat temperature dependence at low temperatures and melting peaks at temperatures greater than 3 K. This behavior continued for coverages up to one complete monolayer (~ 0.11 Å^{-2}). With further coverage increase the additional atoms again showed an interacting Fermi gas behavior down to 0.4 K and again, a should around 0.1 K. For ^{3}He in Anopore there appears to be no extended region of dominant T^2 dependence, and the shoulder temperature location is thickness dependent.

Evidently, helium in Anopore belong to the "class" of films that are adsorbed in heterogeneous substrates. Brewer and co-workers studied near monolayer ^{3}He coverages in porous Vycor glass between 1 and 4 K.[21] The specific heat was well described by a T^2 dependence (2D solid) with an additional constant term which indicates that something must take place to ensure that $C=0$ at $T=0$ K. While there have been no lower-temperature specific-heat studies for ^{3}He films on Vycor, extensive heat-capacity studies with localized ^{4}He films exist. Tait and Reppy[10] found a $T+T^2$ temperature dependence for thin films down to ~ 0.3 K. Below a coverage-dependent temperature, the heat capacity decreased quite sharply; such a break has been followed to temperature as low as 10 mK.[11] The results of Finotello *et al.*[12] for ^{4}He on Xerogel porous glass found a specific-heat bump with similar temperature dependence with coverage which, as in Vycor, disappeared when the film became superfluid.

A way to consider the effect of strong substrate localization is to assume that the atoms are within potential wells of linear dimensions equal to the surface roughness with the depth of the well quantifying the van der Waals attraction to the substrate. The temperature width of the bump corresponds to excitations from the ground to the first excited state and varies inversely with the mass. For ^{4}He films in Anopore, the energy difference would be ~ 0.3 K,[9] which is comparable to the bump's width. However, because of the lower mass, the model would predict a wider bump for ^{3}He films, which is contrary to our observations.

The behavior of helium films on heterogeneous substrates originally studied by Stewart and Dash,[20] was extended by Roy and Halsey[30] and Daunt[31] and later applied by Tait and Reppy.[10] The model assumes that the fluctuations in the adsorption potential are not random and the adsorbed atoms form solidlike patches with a Debye type of heat capacity. With increasing temperature, atoms are promoted out of the patches and into a 2D free-particle state. The specific heat is given by[10]

$$C=A(\Delta/k_BT+2)\exp\{-\Delta/k_BT\}+BT^2\ ,$$

$$T<T_C\ ,\ \Delta\gg k_B\ , \quad (5)$$

$$C=ET+FT^2\ ,\ \ T>T_C,\ \Delta\ll k_B\ . \quad (6)$$

Δ is the energy gap between the 2D solid patches and the free-particle state while T_C is a cutoff temperature that decreases with coverage. The heat capacity receives contributions from the 2D solid patch (T^2 term) and from atoms being excited into a free particle (or extended state) which is approximated by the exponential term at low temperatures and the linear term at high temperatures. As the coverage increases the patches grow; the energy gap decreases and disappears.

Although the model was used to explain the behavior of localized ^{4}He films, it is essentially a fermion model with single occupancy states for $T<\Delta/k_B$, thus, it should also be applicable in the ^{3}He case. When this is done and the ^{3}He films' heat capacity is fitted according to Eq. (5), as shown by the solid lines in Fig. 5, Δ/k_B decreases from 16 to 0.5 K with an increase in coverage from 15.04 to 32.55 μmol/m^2 as seen in the inset to Fig. 5 and summarized in Table I. The coverage dependence of Δ/k_B can be fit by a power law $\Delta/k_B \sim n^{-4.5}$. Taken at face value, these results would be consistent with a model of islands growth with the consequent narrowing of the energy gap as the film thickens. Note that due to the actual magnitude of Δ/k_B, the applicability of Eq. (6) is limited to temperatures ($\Delta \ll k_BT$) higher than probed.

Although reasonable fits are achieved and the behavior of Δ/k_B with coverage is as expected, it decreases too slowly. The monolayer coverage is exceeded long before Δ/k_B becomes vanishingly small. Using the estimate of 18.3 μmol/m^2 for one solid layer with additional liquid layers of 8.4 μmol/m^2, the 32.55-μmol/m^2-thick film corresponds to roughly 2.7 layers. If the entire film were taken as solid, it would amount to 1.8 layers. In both cases, the film is too thick for islands to still be present. Combining with the ^{4}He results (see Table I),[9] one must conclude that an island's type of film growth model may only partly explain the present results. For islands to form on the atomic scale, Δ must be comparable to the bare van der Waals constant so that atoms will energetically prefer to group together because of the disorder rather than spread across the surface. The specific-heat bump is a property of the excitation spectrum of the normal fluid.

A gap in the film's excitation spectrum should eventually disappear as the lower energy states fill and the

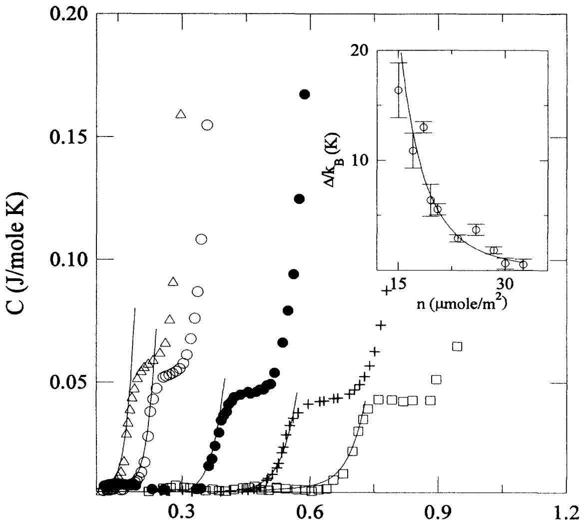

FIG. 5. Fits to Eq. (5) indicated by solid lines. Inset: coverage dependence of the fit parameter Δ/k_B. The solid line is a power-law fit.

higher states become more favorable. It is then possible to extrapolate the linear fits for the area under the bump and its width to zero, Eqs. (2) and (3), as indicated in Fig. 3. The area vanishes at 39.2 μmol/m^2 while the width of the bump narrows to zero at 41.4 μmol/m^2, basically identical results given the uncertainty associated with the linear background choice. In Fig. 6 we plot the bump temperature position dependence on coverage. From this plot it is not clear whether the bump goes to zero at $T=0$ or disappears at a finite temperature. The temperature position of the bump can be characterized by a power law in coverage with $T_B \sim n^{-4/3}$ for ^{4}He and $T_B \sim n^{-9/4}$ for ^{3}He films in Anopore. Assuming the bump disappearance at 40 μmol/m^2 and extrapolating form the power-law behavior, the lowest temperature bump would appear at $T=0.08$ K. Unfortunately, we were unable to obtain reliable data well below 0.1 K as required.

Finally, while the features in the specific heat for localized ^{4}He films in Vycor and Xerogel porous glasses dependence on coverage and eventual disappearance is similar to that of the specific-heat bump in Anopore, Millipore, and Mylar, the nature of the superfluid transition in these substrates is rather different. Vycor and Xerogel are known to exhibit a 3D bulklike transition[32] while films in Anopore, Millipore, and Mylar are 2D-like.[22,33,34] In the latter, the low-temperature shoulder is overtaken by the superfluid transition and a growing specific-heat peak, centered at a temperature above the superfluid transition, appears. In porous glasses the superfluid transition is characterized by a small peak.[32] In contrast, the ^{3}He bump continuously shifts to lower temperature for higher coverages uninterrupted by a superfluid transition. Another difference, as shown in the inset to Fig. 4, is that the ^{3}He heat capacity at constant temperature continuously increases with coverage. Heat-capacity isotherms for ^{4}He in Vycor reveal a peak that signals the superfluid onset;[10,32] for ^{4}He in Anopore, the heat capacity either increases or decreases[9] depending on temperature. More importantly, the lack of a round peak in ^{3}He films supports our interpretation that the ^{4}He specific-heat round peak is a 2D superfluid effect.

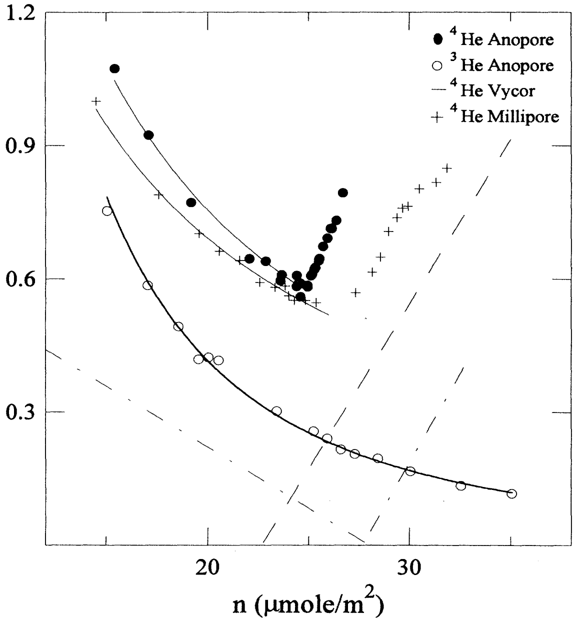

FIG. 6. Coverage dependence of the (middle) temperature position of bump for ^{3}He and ^{4}He in Anopore and ^{4}He in Millipore. Also shown are the superfluid peak temperature position for ^{4}He films in Anopore and Millipore (Ref. 21). Solid lines through the data are results are power-law fits. The dash-dotted lines represented the coverage dependence of the break in Vycor (Refs. 10 and 11) and the superfluid transition line (Ref. 32). The dashed line represents the superfluid transition for Millipore (Ref. 33).

IV. SUMMARY

We have presented a systematic heat-capacity study of ^{3}He films adsorbed on Anopore filters as a function of temperature and thickness. A heat-capacity bump is found for all coverages (thickness). It is centered at a temperature that decreases with increasing coverage as previously found for ^{4}He films. For ^{4}He films, the bump disappears and a round heat-capacity peak shifting to higher temperatures with coverage is seen. No such peak is present in ^{3}He films; the ^{4}He round peak is a manifestation of the 2D superfluid transition.

Films in Anopore were shown to behave distinctly from those on homogeneous surfaces like graphite and thick ^{4}He films. Results were analyzed using a model for islands type of growth of the film originally used for submonolayer ^{4}He films in Vycor. The low temperature rise in the heat capacity can be reasonably fit with this model. An energy gap, Δ, is found to sharply decrease as the bump moves to lower temperature. This is expected as islands grow in size with increasing coverage. However, such a bump is retained for coverages much larger than a monolayer. The existence of a heat-capacity bump cannot be attributed to an island type of growth, rather, it is the consequence of a gap in the normal fluid excitation spectrum.

If an excitation with a gap is present, then, at some coverage the gap should disappear as the higher state becomes energetically more favorable. Extrapolating the width and area of the bump to zero and estimating from the temperature dependence on coverage, the bump should disappear at a coverage $n \sim 40$ μmol/m^2 (~ 3.6 layers) and $T \cong 0.08$ K. This is in contrast to Vycor[11] where the break in temperature dependence goes to zero. See Fig. 6.

The heat-capacity bump is viewed as a universal property of localized (or normal) helium films on disordering substrates. The magnitude of the parameters characterizing it are substrate and isotope dependent. For the same substrate, Anopore, and equivalent coverages, the bump appears at a lower temperature and it is narrower in ^{3}He films. The ^{3}He and ^{4}He coverage dependence of the bump temperature location can be characterized by a power law with the ^{3}He having the larger exponent. Although the van der Waals attraction to the substrate does not distinguish between isotopes, ^{3}He has a smaller mass and thus a larger zero-point motion. However, if the only difference in both systems was the larger zero-point motion of the ^{3}He, then we would expect its bump to appear at lower temperatures than a corresponding ^{4}He film, but retain a similar exponent for the coverage dependence. It is unclear if the exponent indicates a real difference between normal ^{4}He and ^{3}He films or is a consequence of the limited range of the ^{4}He power-law fit.

For future work it is necessary to reduce the addendum heat capacity of the cell and reliably extract the low-temperature heat-capacity temperature dependence. This is important to compare with theoretical predictions of a disorder-induced linear specific heat. Probing lower temperatures would allow one to determine the onset of the bump behavior. Preplating with nitrogen or hydrogen, thus smoothing out the substrate, would help to better quantify the influence of the underlying potential. Different preplated thicknesses would be an effective way to tune the amount of disorder. NMR studies would be useful to determine the degree of localization that the substrate induces on the ^{3}He. It would provide useful structural information on the nature of ^{3}He film.

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