Heat-Capacity Studies of ^{3}He in ^{3}He-^{4}He Mixture Films and the Coverage Dependence of the Two-Dimensional ^{3}He Landau Fermi-Liquid Parameters

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The heat capacity of ^{3}He in ^{3}He-^{4}He mixture films on a nuclepore substrate is reported over the temperature range $90 < T < 124$ mK, for ^{3}He coverages between 0.05 and 1.4 bulk-density atomic layers, and a ^{4}He film thickness of 4.33 bulk-density atomic layers. A step structure appears in the specific heat as a function of ^{3}He coverage. Combining NMR and specific heat data for ^{3}He atoms on the same substrate and for the same ^{4}He coverage allows the two-dimensional Landau Fermi-liquid parameters F_0^A and F_1^S to be extracted as a function of ^{3}He coverage. We conclude that in the submonalayer ^{3}He coverage regime p-state pairing is favored.

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The addition of ^{3}He atoms to bulk liquid ^{4}He generally results in a bulk liquid mixture of the two isotopes of ^{3}He. Under the right conditions of temperature and concentration this mixture can phase separate with the ^{3}He-rich phase above the ^{3}He-poor phase. For very small additions of ^{3}He and for temperatures below ~150 mK, the ^{3}He atoms reside atop the bulk ^{4}He in a bound state known as an Andreev state [1], forming a two-dimensional Fermi system [2]. The addition of ^{3}He atoms to a thin ^{4}He film also results in a two-dimensional Fermi liquid that can be studied over a range of temperature and ^{3}He coverage [3–5]. The ^{3}He atoms occupy a quantum state at the surface of the film and the potential in which they reside can be modified by changing the ^{4}He film thickness [6,7]. Such a system provides a tunable environment for the study of Fermi systems in two dimensions. In the mixture films, the ^{3}He-^{3}He interaction is accompanied by a ^{3}He-^{4}He interaction and modified by the potential imposed by the substrate that supports the ^{4}He film. Thick ^{3}He films, such as bulk ^{3}He, are known to become superfluid at sufficiently low temperatures [8,9], but whether submonolayer ^{3}He films on a ^{4}He substrate can show some form of superfluid behavior is not yet known. Various mechanisms for such behavior have been predicted [10]. The experiments we describe here were designed to further our understanding of the interactions among the ^{3}He atoms on the surface of ^{4}He films. We report measurements [11] of the ^{3}He heat capacity for such mixture films on the porous substrate nuclepore [12]. Comparison of the present results to the results of earlier experiments on the magnetization [13] for these mixture films on the same substrate material at the same ^{4}He coverage allows us to extract the two lowest-order Landau Fermi-liquid parameters for the submonolayer ^{3}He and allows a determination of the strength of the interaction between the ^{3}He atoms. We find that p-state pairing is favored. These results for the strength of the ^{3}He-^{3}He interaction and the favored pairing state provide information that should help to guide investigations that search for superfluidity in this two-dimensional system.

The design of the calorimeter we used to make quasiadiabatic heat-capacity measurements has been shown previously [11]. The substrate is located in an oxygen-free high conductivity copper sample cell and consists of 1416 nuclepore disks each of diameter 2.54 cm. Each disk is center punched and individually pressed onto the copper center post of the sample cell to provide more direct thermal contact between the disks and the cell. The disks are porous, threaded by $\sim 3.5 \times 10^8$ cm^{-2} well-defined pores of nominal diam 200 nm and the total substrate provides an effective surface area of 23.96 m^2 [14]. It has been previously established that for the helium coverages studied here the pore spaces in the nuclepore do not capillary condense [15]. The void space in the sample cell is estimated to be ~3.0 cm^3. The cell is sealed with a small amount of Stycast 2850GT epoxy. A Pt-W heater wire is wound nonmagnetically around the cell and a thin layer of G.E. varnish is applied to improve the thermal contact. A carbon thermometer is bonded in a copper block and the block is clamped to the top post of the calorimeter. This thermometer is calibrated by a Germanium thermometer, which was previously calibrated by a melting curve thermometer. A heat switch [16] connects the sample cell to the mixing chamber of a dilution refrigerator. The ^{4}He film thickness [17] was fixed at 4.33 bulk-density atomic layers throughout this experiment. We estimate that 2.54 ± 0.13 bulk-density ^{4}He atomic layers are solid [18]. The contribution of the ^{4}He film to the total heat capacity is negligible.

To obtain heat-capacity data, a dc heat pulse of typically 150 sec duration is applied to the sample cell and the resulting temperature change of the sample cell is measured. Because the thermal relaxation time between the sample cell and the mixing chamber is much longer than the thermal equilibration time of the sample cell, the temperature response is fitted by a combination of linear background drift and exponential decay. The temperature difference is determined from the difference between the extrapolations of the before and after linear drifts to the middle of each heat pulse. The temperature drift during the time interval of a heat pulse was typically no more than a few percent of the temperature change due to the heat pulse, but under some conditions could be as large as 10% of the temperature change.

In an early experimental run [11] part of the ^{3}He became trapped in the filling capillary and this has been resolved in more recent work by lifting two thermal anchors of the sample filling capillary at the mixing chamber while maintaining the thermal anchor at the warmest heat exchanger to reduce the heat leak. Data obtained before and after this change to the experimental apparatus correlate well, and we have scaled our earlier data to the more recent data by using the location of the step (see below) in the heat-capacity data for internal calibration.

Shown in Fig. 1 is a selected set of some of our heat-capacity data after background subtraction [19] plotted as a function of temperature for several different ^{3}He coverages. When ^{3}He is in the degenerate regime, i.e., $T \ll T_F$, the specific heat of a 2D Fermi liquid is

$$C = \pi k_B^2 m^* A T / 3\hbar^2, \qquad (1)$$

where m^* is the effective mass of a ^{3}He atom (defined below), A is the surface area covered by the ^{3}He atoms, and k_B is the Boltzmann constant. The Fermi temperature is density dependent,

$$T_F = h^2 N_3 / 4\pi k_B m^* A, \qquad (2)$$

where N_3 is the number of ^{3}He atoms. For a ^{3}He coverage of less than 0.1 layer, T_F is not far from the temperature regime of the experiment and thus the specific heat for the data at the lowest ^{3}He coverages studied is independent of temperature and behaves as a two-dimensional Boltzmann gas. Above a ^{3}He coverage of 0.5 layers C/T isotherms at 100 mK [20], Fig. 2, show a steplike increase that comes from the population of the first excited state of the Andreev quantum surface states [21]. This step structure is consistent with the step previously seen in data for the ^{3}He magnetization [13,22] on nuclepore, and the specific heat step observed recently for mixture films by Dann *et al.* [23] on graphite.

By using the known surface area, we can convert the specific heat at 100 mK to the effective mass of ^{3}He, m^* and we show this as a function of ^{3}He coverage in Fig. 3. In a two-dimensional Fermi-liquid model, the effective mass can be written as

$$m^* = m_H(1 + F_1^S/2), \qquad (3)$$

where m_H is the hydrodynamic mass of a ^{3}He atom due to the interactions with the surrounding ^{4}He, and F_1^S is the spin-symmetric Landau Fermi-liquid parameter resulting from the ^{3}He-^{3}He interactions. Extrapolation to the low density limit yields, m_H, $(m_H/m_3) = 1.29 \pm 0.03$, consistent with the earlier NMR results [4,5] on a nuclepore substrate for nearly the same ^{4}He coverage. Several theoretical predictions [24] have been made for m_H and these predictions for the effective mass enhancement are in reasonable accord with the experimental results.

Earlier NMR results exist [5,13] for the magnetization of mixture films on nuclepore for which the ^{4}He coverage of 54 mmol/m^2 was very close to the present value of 55.5 mmol/m^2. In a two-dimensional Landau Fermi-liquid model, the magnetization M, normalized to that for an ideal two-dimensional Fermi gas, M_0, can be written as

$$M/M_0 = (m_H/m_3)[1 - \exp(-T_F/T)] \times [(1 + F_1^S/2)/(1 + F_0^A)]. \qquad (4)$$

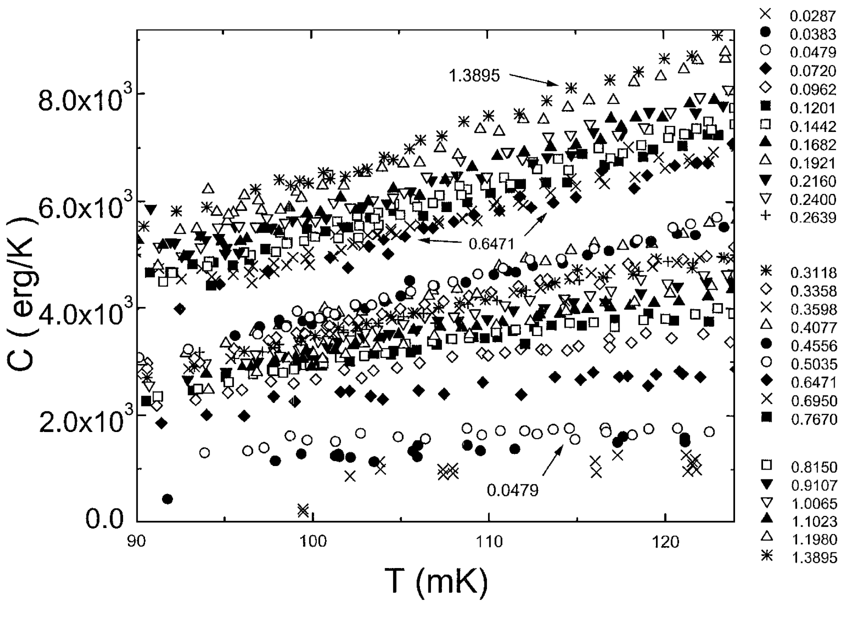

FIG. 1. A selected set of specific heat vs temperature data for various values of the ^{3}He coverage on a 4.33 bulk-density atomic layer ^{4}He film. These data have been corrected for the background specific heat. The legend shows the ^{3}He coverage values in units of bulk-density ^{3}He atomic layers.

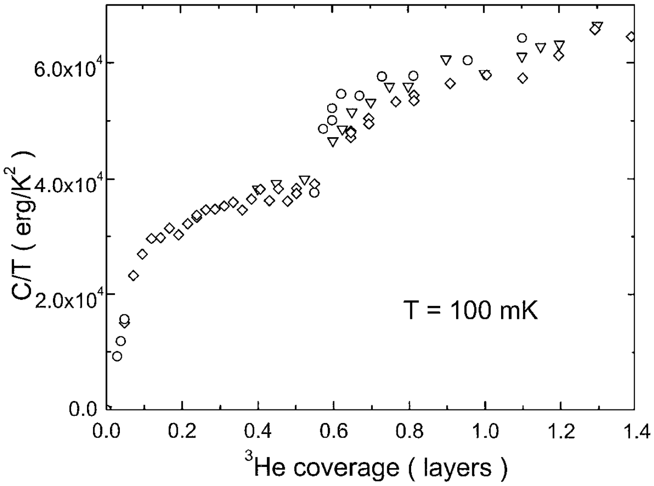

FIG. 2. C/T vs ^{3}He coverage at $T = 100$ mK. Here and in Fig. 3 different symbols represent different sets of data taken on different experimental runs.

Thus from the effective mass and the magnetization, we have two measured parameters for the same substrate material and we can extract the two Landau Fermi-liquid parameters F_1^S and F_0^A for the ^{3}He. Figure 4 shows the resulting values of F_0^A and F_1^S versus ^{3}He coverage. There are theoretical predictions for F_1^S and F_0^A made by Krotscheck *et al.* [25] at a ^{4}He density of 4.44 layers and a ^{3}He coverage of 0.495 layers. The experimental value of F_1^S is close to the theoretical prediction (0.63), but the experimental value of F_0^A is about 3 times smaller than the prediction (-0.85). $-F_0^A$ is proportional to the ^{3}He-^{3}He interaction energy in the $l = 0$ state and $-F_1^S$ to that in the $l = 1$ state. The experimentally extracted Landau parameters allow us to conclude that the s-state interaction is repulsive and the p-state interaction is attractive.

There have been various theoretical predictions [10] relevant to the question of whether or not the ^{3}He that resides in the Andreev surface state can undergo a transition to a superfluid state. These calculations suggest that the interactions among the ^{3}He atoms are repulsive for concentrations exceeding 3%. A repulsive interaction means that s-wave paring is impossible. Theory predicts that p-wave pairing remains repulsive to second order, but Chubukov [26] has included vertex corrections and predicts the possibility of $T_C \sim 10^{-4}$ K for a coverage of 0.3 monolayer. Bashkin [27] pointed out that if attraction were to occur, then the possibility of the formation of dimers [28] would be present and this might result in a transition temperature above 1 mK. To date no superfluid transition has been found [29]. The possibility of superfluidity in the two-dimensional ^{3}He film may be enhanced by the presence of a magnetic field, i.e., for the case of a polarized system. In this case s-wave pairing is suppressed by the field. For p-wave pairing the field promotes short-range attraction but decreases the density of states. These are competing effects. Predictions for T_C for the case of p-wave pairing show a maximum as a function of polarization with $T_C > 1$ mK in a field of ~15 T but such predictions are very sensitive to details [30]. More exotic possibilities that may lead to superfluidity have been discussed [31].

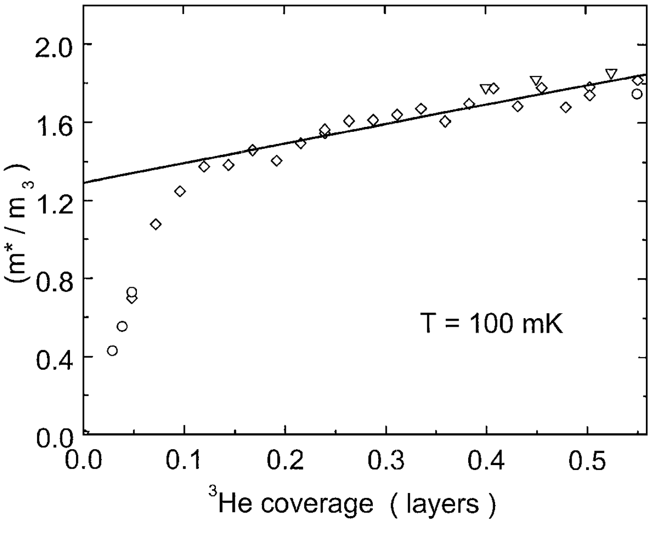

FIG. 3. The ratio of effective mass relative to the ^{3}He bare mass vs ^{3}He coverage for low ^{3}He coverages at $T = 100$ mK.

In conclusion, we have presented heat-capacity data for various ^{3}He coverages for a fixed ^{4}He film thickness of 4.33 bulk-density layers on a nuclepore substrate for $90 < T < 124$ mK. For a ^{3}He coverage <0.1 layers, the ^{3}He behaves as a two-dimensional Boltzmann gas; when the coverage is in the range 0.1–0.55 layer, the ^{3}He resides in a ground state at the surface of the film and behaves as a quasi-two-dimensional Fermi liquid with $m_H = 1.29 \pm 0.03 m_3$ at 100 mK. At least one step in the specific heat is observed, consistent with those observed by magnetization measurements, and attributed to

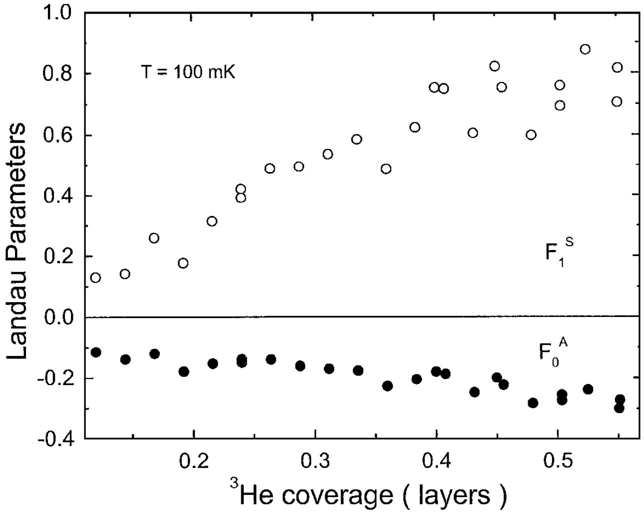

FIG. 4. The Landau parameters F_1^S and F_0^A vs ^{3}He coverage. F_1^S (open circles) values are derived from the current specific heat measurements, and F_0^A (solid circles) values are determined from the combination of earlier NMR data and the data from the specific heat measurements reported here.

the presence of the first and second two-dimensional quantum states. The Landau parameters F_0^A and F_1^S have been extracted from the specific heat and magnetization experiments on nuclepore. The ^{3}He-^{3}He interaction is found to be dependent on the ^{3}He coverage and is repulsive in the *s* state but attractive in the *p* state.

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