Thermodynamic evidence for two dimensional ^{3}He tunnelling excitations

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Abstract

The heat capacity of the second layer solid of ^{4}He adsorbed on graphite has been measured after doping with ^{3}He atoms, in the temperature range 2 - 80 mK. In a series of experiments the ^{3}He coverage was held constant at 1.0 and 0.7 nm^{-2} respectively while the ^{4}He coverage was progressively increased. Heat capacity isotherms show a distinct maximum over the range of coverages for which the second layer commensurate solid is expected to be stable. In this region the heat capacity exhibits a broad maximum near 50 mK, at a value close to k_B per atom. At higher temperatures the heat capacity decreases slowly, while at lower temperatures it tends to zero faster than linearly. Our interpretation is that the excitations are tunnelling ^{3}He quasiparticles in the host 2D crystalline ^{4}He matrix. In this case the bandwidth and effective mass are determined by the sum of all possible cyclic permutations causing a ^{3}He atom to hop from a particular site. The low temperature behaviour indicates a breakdown of the Fermi liquid description arising either from interactions between the excitations or localisation.

Key words:
helium mixtures; two dimensional helium

This paper concerns the properties of monolayer isotopic helium solid mixtures. The atomically flat surface of graphite permits the growth of atomically layered helium films. Here we concentrate on the second layer, where the properties of isotopically pure films have been extensively studied experimentally and the phase diagram calculated theoretically. For both isotopes the layer solidifies into a phase commensurate to the underlying solid first layer, which itself forms a compressed solid on a triangular lattice. At perfect commensuration (C) the ratio of layer densities is 4/7. As the coverage is increased the second layer evolves into an incommensurate solid (IC), before promotion occurs to a third fluid layer.

The present experiment was motivated by the search for delocalised ^{3}He tunnelling excitations in a 2D ^{4}He crystal doped with ^{3}He. In bulk solid ^{4}He the existence of such impuritons is well established at low ^{3}He concentrations [1]. Since bulk solid helium mixtures are unstable with respect to isotopic phase separation at low temperatures, quantum degeneracy is not observable. Earlier work on sub-monolayer films had found evidence both for phase separation and for such tunnelling excitations [2]. We conjectured that in the second layer the significantly larger interatomic tunnelling rates may suppress phase separation, leading to a new state of matter, combining crystalline order with the properties of a quantum liquid: a "Fermi-liquid solid".

The sample chamber is the same as that used in previous work and it permits measurements of both heat capacity and magnetization. The present experiment consists of two runs in which the total coverage was varied from 16.23 to 21.50 nm^{-2}, keeping the ^{3}He coverage constant at either 0.7 or 1.0 nm^{-2} respectively. In Fig. 1 we show the experimental heat capacity isotherms. We can scale coverages from the theoretical phase diagram determined by Path Integral Monte Carlo methods [3], taking promotion to a third fluid layer as a ref-

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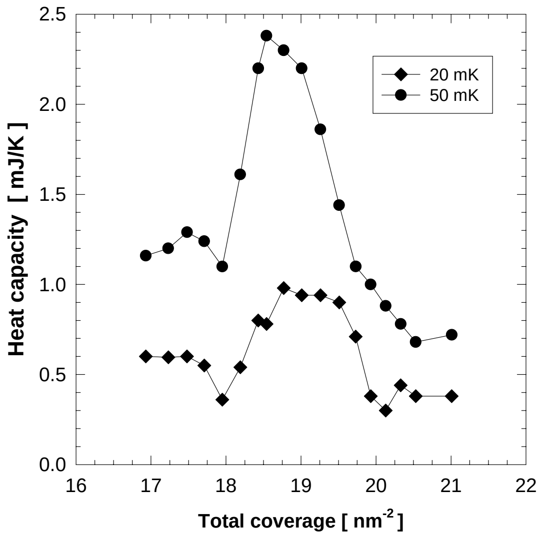

Fig. 1. Heat capacity isotherm, with $n_3 = 0.7$ nm^{-2}

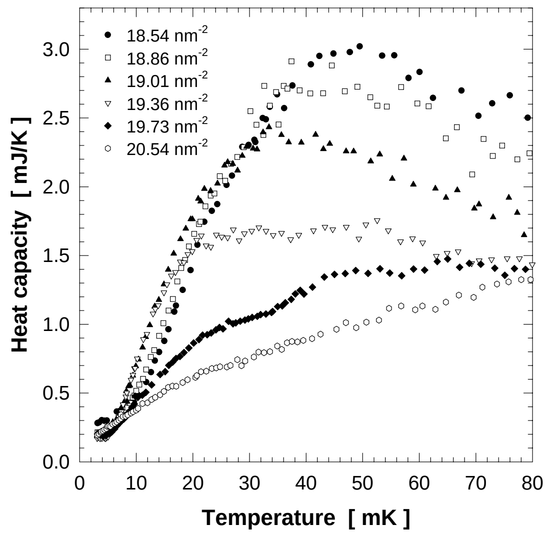

Fig. 2. Heat capacity with $n_3 = 1.0$ nm^{-2} for various total coverages

erence point. The experimental signature is the break in the isotherms at 20 nm^{-2}, which the PIMC calculations find at 21.2 nm^{-2} for an assumed density of the compressed first layer of 12.7 nm^{-2}. The scaled theoretical phase boundaries are then (i) between a uniform liquid phase and a coexistence of liquid plus commensurate solid at 17.96 nm^{-2}, (ii) a C phase centred on 18.9 nm^{-2} and of width 0.6 nm^{-2} and (iii) a region of C-IC coexistence from 19.2 to 19.8 nm^{-2}. The scaled density of the compressed first layer is 12.0 nm^{-2}.

The striking feature of the isotherms above 30 mK is the large heat capacity observed over the region of stability of the C-solid. In Fig. 2 the temperature dependence of data at a selection of total coverages with $n_3 = 1.0$ nm^{-2} is shown. In this temperature regime the heat capacity is close to the value for a classical gas. The heat capacity is significantly greater for $n_3 = 1.0$ nm^{-2} relative to 0.7 nm^{-2}, but the scaling is not perfect. As the coverage is increased through the region of expected C-IC coexistence the heat capacity drops. The set of data at 20.5 nm^{-2}, following promotion, shows a linear heat capacity as expected for a Fermi fluid. In the C-phase the heat capacity decreases faster than linearly at the lowest temperatures. Also at the highest temperatures the heat capacity decreases somewhat.

The unusually high heat capacity in the C-phase suggests that, as originally conjectured, in the absence of crystalline disorder the ^{3}He atoms form a band of tunnelling excitations. On a triangular lattice we expect a bandwidth $\Delta = 4t$, where the tunnelling rate $t = J_2 + 2J_3 + 4J_4 + ...$ is determined by the sum of all possible cyclic permutations moving a ^{3}He atom from a particular site. A sufficiently large bandwidth will inhibit phase separation. The other characteristic energies of the problem are U, an interaction energy between ^{3}He impurities, and the degeneracy temperature of the gas, $T_F = \sqrt{3\pi t x}$, where x is the ^{3}He concentration. For $E_F/\Delta \sim 0.1$, neglecting interactions, our numerical calculations for a Fermi gas show that the heat capacity peaks at a value of order k_B per ^{3}He atom, at $T/\Delta \sim 0.1$, subsequently decreasing as observed.

Within this simple model we expect a linear heat capacity when $T \lesssim T_F$, arising from a degenerate Fermi gas of excitations with effective mass $m^* = 2\hbar^2/3a^2t$. In contrast we observe a faster than linear decrease, showing that a Fermi liquid is not formed. This may be attributable to interactions between ^{3}He impurities (for example due to overlapping lattice strain fields) or localisation due to substrate disorder, introducing spatial variations in the tunnelling rate. Alternative ground states of the system incompatible with the present data are: a homogeneous solution of localised ^{3}He spins; ^{3}He phase separated into 2D solid clusters. A further possible scenario is that phase separation occurs into ^{3}He liquid clusters, but this is not supported by preliminary magnetisation data.

References

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