Properties of two-dimensional ^{3}He in ^{3}He - ^{4}He mixture films

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Abstract

^{3}He atoms on a superfluid ^{4}He film provide a unique example of an interacting two-dimensional Fermi system. NMR and specific heat experiments on this system reveal a number of its detailed properties. For low ^{3}He coverages changes in the ^{4}He substrate coverage allow the energetics of the ^{3}He to be determined and a localization transition is seen as a function of the ^{4}He coverage. As the ^{3}He coverage is increased, the two-dimensional ^{3}He system evolves from a very dilute Fermi gas to an interacting two-dimensional Fermi liquid. A combination of NMR and specific heat measurements results in a determination of the ^{3}He coverage dependence of the two lowest order Landau Fermi liquid parameters, F_0^a and F_1^s. Further increases in the coverage result in a discrete step in the magnetization and the specific heat due to the occupation of a second quantum state. The subject is surveyed here very briefly.

Key words: helium3; two-dimensional; films; Fermi

1. Introduction

The addition of small numbers of ^{3}He atoms to ^{4}He at low temperatures results in the occupation of a surface state at the free surface of the bulk liquid. This surface state was first identified by Andreev[1] and arises because of the larger zero point motion for the ^{3}He relative to the ^{4}He and a resulting potential well at the free surface. David Edwards and his colleagues explored many of the properties of the ^{3}He in this system[2] on the bulk free surface. For the case of small amounts of ^{3}He in thin ^{4}He films at low temperature the atoms occupy a surface state much like that on the bulk free surface and constitute a very nearly ideal two-dimensional Fermi gas[3,4]. In this case the presence of the substrate makes the potential more complicated and quite distinct particle-in-a-box excited states can exist if the ^{4}He film thickness is in the right range[5]. Krotscheck[6] and and Treiner[7] and their colleagues studied this theoretically and predicted the quantum state energies as a function of ^{4}He coverage for the ^{3}He low-coverage limit. Here we will review[8,9] a number of the interesting properties of these two-dimensional ^{3}He with an emphasis on recent work, draw together some recent results from several investigators to comment on the Fermi liquid parameters, and speculate about possible future directions.

For the ideal two-dimensional Fermi gas in the absence of interactions, the ^{3}He atoms on a ^{4}He film can be described by their bare mass, m_3. In this idealized picture, the Fermi degeneracy temperature is given by $T_F = h^2 N_3/4\pi k_B m_3 A$ where N_3 is the number of ^{3}He atoms and A is the area occupied by the ^{3}He atoms. For $T < T_F$ the specific heat is given by $C = \pi k_B^2 m_3 AT/3\hbar^2$ and the magnetic susceptibility at $T = 0$ is given by $\chi_0 = (m_3 A\mu^2/\pi\hbar^2)$, where μ is the magnetic moment of a ^{3}He atom. In the two-dimensional degenerate limit, the specific heat and the magnetic susceptibility are independent of the number of ^{3}He particles in the system, a result that is perhaps somewhat counter-intuitive. Of course, any such real system suffers from interactions and these must be properly taken into account. The ^{3}He atoms can interact with the ^{4}He atoms at the surface of the film and also with each other. The effect of interactions with the ^{4}He is taken into account by the introduction of the hy-

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drodynamic mass, $m_h > m_3$, and the ^{3}He - ^{3}He interactions are included to low order by the introduction of Landau Fermi liquid parameters F_0^A and F_1^S. With these changes, the specific heat can be written as $C = \gamma(1 + F_1^S/2)T$ where $\gamma = \pi k_B^2 m_3 A/3\hbar^2$ and at finite temperature the magnetic susceptibility χ, normalized to that for an ideal two-dimensional Fermi gas, χ_0, can be written as $\chi/\chi_0 = (m_h/m_3)[1 - exp(-T_F/T)][(1 + F_1^S/2)/(1 + F_0^A)]$.

2. NMR Experiments

Measurements of the magnetic susceptibility have documented the increasing strength of the ^{3}He - ^{3}He interactions with increasing ^{3}He coverage (Fig. 1), and also revealed a striking step structure[10]. Above about 0.1 layer of ^{3}He there is a nearly linear increase in the susceptibility. Extrapolation to zero coverage allows an estimate of m_h and we see that (Fig. 1, inset b) this is dependent on the ^{4}He coverage. This dependence is understandable because as the ^{4}He film thins, the ^{3}He atoms find themselves in an increasingly structured environment and this enhances m_h. Behavior of this sort is evident in the theoretical work of Krotscheck and his colleagues. The step structure is a result of the population of the first excited state for the ^{3}He in the potential provided by the substrate and the underlying ^{4}He. The addition of atoms to this state populates a second two dimensional world. This second state provides its own separate contribution to the magnetization and this is the origin of the step. One can also think in terms of a Fermi sphere that in two dimensions is reduced to a populated disk. Addition of ^{3}He atoms ultimately introduces a second disk, the population of which contributes separately to the magnetization[9].

For ^{3}He coverages of 0.1 atomic layers, where the interactions are small, it is possible to determine the explicit energy of the ground and first excited states by measurements[11] of the NMR relaxation times, and to do so as a function of ^{4}He coverage. In Fig. 2 we show the measured energy of the ^{3}He in the ground state and in the first excited state as a function of the ^{4}He coverage. Structure is evident. Comparison to the theoretical predictions[6,7] of Krotscheck and Treiner is shown by the solid and dashed lines. As the potential available for the ^{3}He in the excited state grows more narrow with decreasing ^{4}He coverage, the energy rises and the state eventually is no longer bound.

It is also interesting to ask about the behavior of the ^{3}He laterally along the film surface. When the ^{4}He film is relatively thick, the ^{3}He is rather free to move along the ^{4}He film. A conceptual question is, if the ^{4}He film is reduced in thickness, might not the ^{3}He atoms begin to feel the semi-solid ^{4}He underlayer and find their lateral mobility restricted. This can be determined with NMR by measurements of the spin diffusion coefficient, D_S. An example of such a measurement[12] is shown in Fig. 3 where we show the measured NMR spin diffusion coefficient. The spin diffusion coefficient falls dramatically over a very narrow range of decreasing ^{4}He film thickness. This is reminiscent of a mobility edge in the case of a conducting system. We interpret this to mean that with decreasing ^{4}He coverage the ^{3}He atoms feel increasing interaction with the semi-solid substrate and tend to become localized. Evidence for this interpretation also comes from the temperature dependence of the susceptibility[12]. Also shown on the figure is the ^{4}He coverage above which the ^{4}He film is superfluid

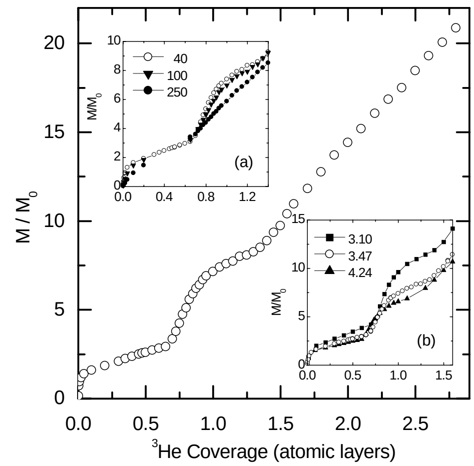

Fig. 1. The normalized magnetic susceptibility of ^{3}He atoms on a ^{4}He film as a function of the ^{3}He coverage for $T = 40$ mK shows a clear step structure. The insets show (a) the step at $D_4 = 3.47$ (bulk density) atomic layers for T = 40 mk, 100 mK, and 250 mK, and (b) the step at $T = 40$ mK for three dif
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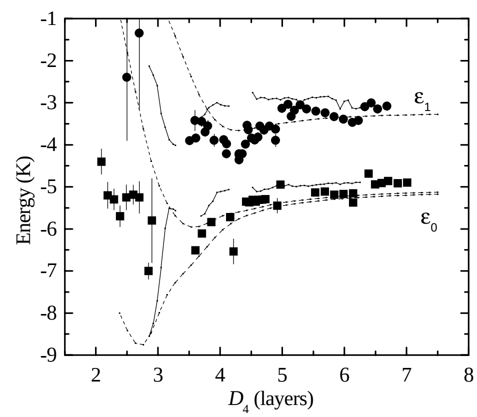

Fig. 2. The energy of the ^{3}He in the ground and first excited states as a function of the ^{4}He film thickness. Theoretical predictions dure to Krotscheck (solid lines) and Treiner (dashed liines) are also shown.

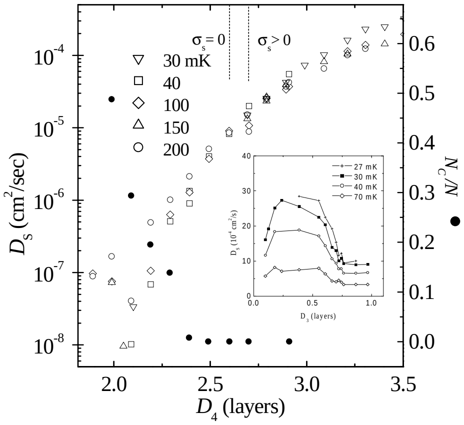

Fig. 3. The spin diffusion coefficient for 0.1 layer of ^{3}He as a function of ^{4}He coverage. Due to the tortuosity ϕ of the substrate (in our case Nuclepore for which $\phi \approx 14$) the bare spin diffusion coefficient $\mathcal{D}$ is expected to be $\mathcal{D} = \phi D_S$. The Curie fraction, N_C/N is also shown[12]. The inset shows D_S as a function of ^{3}He coverage[13]. The peak in the inset data has been explained by recent theoretical calculations[15].

($\sigma_s > 0$) at 100 mK as determined by a simultaneous third sound measurement in the same sample cell on an adjacent Nucleore substrate. The NMR spin diffusion coefficient appears unaffected by the presence of the superfluid transition. Since the diffusion is influenced by scattering and the superfluid transition is a vortex unbinding transition, this is not surprising.

Diffusion measurements have also been carried out as function of the ^{3}He converage in an effort to document the effect of increasing interactions on the diffusion. The result of such a study[13] is shown in the inset to Fig. 3. The unexpected presence of a peak in the diffusion coefficient as a function of ^{3}He coverage, not predicted by earlier theoretical work[14], has recently been shown to be consistent with Fermi liquid theory[15], possibly signaling the presence of a spin-viscous damping mechanism in the two-dimensional system.

3. Specific Heat and Landau Parameters

Recently new specific heat experiments[16,17] have added to our understanding of this system. Above a ^{3}He coverage of 0.5 layers C/T isotherms show a step-like increase that comes from the population of the first excited state of the Andreev quantum surface states. This step structure is consistent with the step previously seen in data for the ^{3}He magnetization.

Our new work[17,18] on the heat capacity of mixture films allows us to determine the two most important Landau Fermi liquid parameters, F_0^A and F_1^S. The heat capacity gives us $m^* = m_H(1 + F_1^S/2)$ and the magnetization M, normalized to that for an ideal two-dimensional Fermi gas, M_0, can be written as $M/M_0 = (m_H/m_3)[1-exp(-T_F/T)][(1+F_1^S/2)/(1+F_0^A)]$. Thus we can extract the two Landau Fermi liquid parameters F_1^S and F_0^A for the ^{3}He from data for C/T and M_0/M on the same substrate. Fig. 4 shows the resulting values of F_0^A and F_1^S versus ^{3}He coverage from our measurements[10,17,18]. Theoretical predictions by Krostcheck are in accord with the results. New experimental work has begun at much lower temperatures and is expected to c

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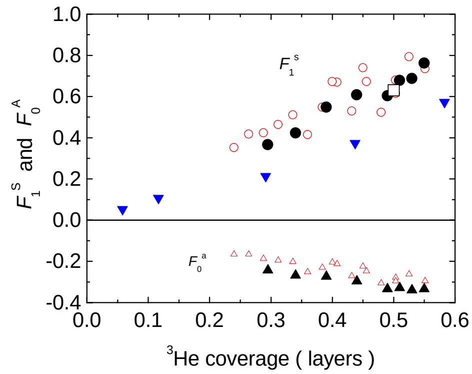

Fig. 4. The Landau Fermi liquid parameters F_0^a (triangles) and F_1^s (circles) as a function of ^{3}He coverage for the case of a ^{4}He substrate of 4.33 bulk-density layers. Also shown are theoretical predictions for F_1^s (square) and the results for F_1^s (inverted triangles) from Saunders and collaborators[16].

4. Future Work

In the area of mixture films there are predictions of a transition to superfluid behavior in the two-dimensional ^{3}He that resides on the ^{4}He film at low temperature. Estimates of the transition temperature for superfluidity were first made in the ^{3}He in bulk ^{3}He-^{4}He mixtures and have been pessimistic, ranging from 10^{-5} - 10^{-4}K for s-wave pairing at low concentrations[19–21] to 10^{-10} - 10^{-4}K for p-wave pairing at higher concentrations. Application of a magnetic field does not improve the s-wave case, but brings the p-wave estimate[21,22] to 10^{-5} - 10^{-4}K. Experiments have found no evidence for a transition. For the attractive case, T_c is predicted[23,24] to be ~ 1 mK for 0.01 monolayer ^{4}He; for higher concentrations the prediction[25] yields 10^{-4}K for 0.3 monolayer. Baskin[26] and colleagues[20] suggest ^{3}He dimers[27] may form and result in a KT transition in the 1 - 5 mK range. Pobell's group found[28] no evidence for superfluidity in 2D solutions for T $\geq$ 0.9 mK in zero magnetic field with ^{3}He coverages in the range 0.1 to 1.0 monolayer, and in unpublished work Saunders group has found no evidence for dimers[29] at higher temperatures. The most optimistic predictions[22] are for the case of finite field, where for low coverages in a field of 15T a transition is expected in the range 1 - 10 mK. Other coverages are predicted to produce T_c values that may be accessible. One must take all such predictions with some care since not all the the parameters relevant to the predictions of T_c can be calculated theoretically[30].

$-F_0^A$ is proportional to the ^{3}He -^{3}He interaction energy in the l = 0 state and $-F_1^S$ to that in l = 1 state. Based on this work (Fig. 4) we can conclude that for our coverages, any potential superfluid state for the ^{3}He will be p-wave, in accord with recent theoretical predictions[30].

Somje rather exotic speculations exist. For the case of a dilute mixture film on a cesium substrate it is possible that for appropriate coverages of ^{3}He one might be able to populate both the film surface state and the "substrate state" between the ^{4}He film and the cesium. In such a case one might have two two-dimensional ^{3}He films adjacent to each other. By tuning the ^{4}He film thickness one might be able to tune the excitations and interactions between the two two-dimensional sets of ^{3}He atoms. No theoretical investigation of this as a possible candidate for superfluidity has been carried out.

Unusual behavior of ^{3}He - ^{4}He mixture films on hydrogen substrates has also been observed. Chen et al.[31] have reported the presence of two Kosterlitz-Thouless-like transitions. More recently, in addition to a Kosterlitz-Thouless transition, a non-Kosterlitz-Thouless-like decoupling feature has been seen[32] in quartz crystal microbalance experiments in mixture films on hydrogen. Other interesting behavior has also recently been seen[33] on hydrogen.

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References

[1] A.F. Andreev, Zh. Eksp. Teor. Fiz. **50** (1966) 1415; Sov. Phys. JETP **23**, (1966) 939.

[2] D.O. Edwards, W.F. Saam, *Prog. Low Temp. Phys.*, vol. VIIA, ch. 4, p. 284, ed. D.F. Brewer, (North Holland, 1978).

[3] B.K. Bhattacharyya, M.J. DiPirro, F.M. Gasparini, Phys. Rev. B **30** (1984) 5029.

[4] J.M. Valles, Jr., R.H. Higley, B.R. Johnson, R.B. Hallock, Phys. Rev. Letters **60** (1988) 428.

[5] F.M. Gasparini, B.K. Bhattacharyya, M.J. DiPirro, Phys. Rev. B **29** (1984) 4921; D.S. Sherrill, D.O. Edwards, Phys. Rev. B **31** (1985) 1338.

[6] E.M. Krotscheck, Phys. Rev. B **32** (1985) 5713; B.E. Clements, E. Krotscheck, M. Saarela, Phys. Rev. B **55** (1997) 5959.

[7] N. Pavloff, J. Treiner, J. Low Temp. Phys. **83** (1991) 331.

[8] R.B. Hallock, *Prog. Low Temp. Phys.*, ed. W.P. Halperin, (North Holland, Amsterdam), vol. XIV, ch. 5, 321-443, 1995, and references therein.

[9] R.B. Hallock, *Physics Today*, **51** (1998) 30.

[10] R.H. Higley, D.T. Sprague, R.B. Hallock, Phys. Rev. Letters, **63** (1989) 2570.

[11] N. Alikacem, D.T. Sprague, R.B. Hallock, Phys. Rev. Letters, **67** (1991) 2501; D.T. Sprague, N. Alikacem, P. Sheldon, R.B. Hallock, Phys. Rev. Letters, **72** (1994) 382.

[12] P.A. Sheldon, R.B. Hallock, Phys. Rev. Letters **77** (1996) 2973.

[13] P.A. Sheldon, R.B. Hallock, Phys. Rev. Letters **85** (2000) 1468.

[14] K. Miyake, W.J. Mullin, J. Low Temp. Phys. **56** (1984) 499.

[15] P.F. Farinas, Phil. Mag. Lett. **81** (2001), 719.

[16] M. Dann, J. Nyeki, B.P. Cowan, J. Saunders, Phys. Rev. Letters **82** (1999) 4030.

[17] P.C. Ho, R.B. Hallock, Phys. Rev. Letters **87** (2001) 135301; P.C. Ho, H, Akimoto and R.B. Hallock, J. Low Temp. Phys. **126** (2002) 349.

[18] H. Akimoto, R.B. Hallock, this volume.

[19] E. P. Bashkin, A. E. Meyerovich, Adv. Phys. **30** (1981) 1.

[20] E. Østgaard, E. P. Bashkin, Physica B **178** (1992) 134.

[21] P. G. van de Haar, G. Frossati, K. S. Bedell, J. Low Temp. Phys. **77** (1989) 35.

[22] M. Y. Kagan, A. Chubukov, JETP Lett. **47** (1988) 614.

[23] M. Y. Kagan, A. Chubukov, JETP Lett. **50** (1989) 517.

[24] M. Y. Kagan, Soviet Physics - Uspekhi **37** (1994) 69.

[25] A. V. Chubukov, Phys. Rev. B **48** (1993) 1097.

[26] E. P. Bashkin, Sov. Phys. - JETP **51** (1980) 181.

[27] E. Krotscheck, J. Paaso, M. Saarela, K. Schrkhuber, Phys. Rev. Letters **85** (2000) 2344.

[28] K. Shirahama, F. Pobell, Physica B **194** (1994) 863.

[29] J. Saunders (private communication).

[30] D.V. Efremov, M.S. Mar'enko, M.A. Baranov, M.Y. Kagan, preprint (to be published in Physica B).

[31] M.-T. Chen, J. M. Roesler, J. M. Mochel, *J. Low Temp. Phys.* **89** (1992) 125.

[32] P.S. Ebey, P.T. Finley, R.B. Hallock, J. Low Temp. Phys. **110** (1998) 635; and unpublished.

[33] G.A. Csathy, E. Kim and M.H.W Chan, Phys. Rev. Letters, **88**, (2002) 045301.