LA-UR 93-1414

Conf-930367--4

Los Alamos National Laboratory is operated by the University of California for the United States Department of Energy under contract W-7405-ENG-36

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SUBMITTED TO Conference on Spectroscopies in Novel Superconductors, Santa Fe, Nm, March 17-19, 1993

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MASTER

Similarity of the Leading Contributions to the Self-Energy and the Thermodynamics In Two- and Three- Dimensional Fermi Liquids

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ABSTRACT - We compare the self-energy and entropy of a two- and three- dimensional Fermi Liquids(FLs) using a model with a contact interaction between fermions. For a two dimensional(2D) FL we find that there are T^2 contributions to the entropy from interactions separate from those due to the collective modes. These T^2 contributions arise from non analytic corrections to the real part of the self-energy and are analogous to $T^3 lnT$ contributions present in the entropy of a three-dimensional(3D) FL. The difference between the 2D and 3D results arises solely from the different phase space factors.

Keywords: Two Dimensions, Fermi Liquids, Thermodynamics

The 2D nature of the cuprate superconductors naturally leads to a FL model for the normal state properties. The doping dependence of the magnetic susceptibility, the thermopower and the Hall resistivity have been successfully explained on the basis of FL theory by Trugman[1990] as has NMR data [Monthoux 1992] Other experimental data is more difficult to describe with the low temperature and energy expressions which are usually taken to characterise a FL. This has lead to speculations that the ground state of the electronic degrees of freedom in the cuprate planes is not a FL. One proposal is motivated by 1D results in which the ground state is a Luttinger Liquid(LL).[Anderson 1990] This requires that 1D results may be extended to 2D. There has also been developed a phenomenology which attempts to describe the apparently non FL like experimental results.[Varma 1989 and Schmitt Rink 1989] There is as yet no microscopic basis for this phenomenology on a lattice. These speculations have lead to a search for the breakdown of FL in 2D.[Serene 1991, Fukuyama 1991 and Engelbrecht 1992] To date no evidence has been found.

In 3D it is well known that the leading corrections to FL behavior come from long wavelength fluctuations. Here we investigate these effects for a 2D FL. Calculating these terms for a 1D FL in perturbation theory one immediately finds that the corrections are more important than the leading linear dependences in the self energy and the specific heat. This signals the breakdown of the 1D FL which is consistent with the exact results for 1D systems. One might expect then that perturbation theory would show evidence for a breakdown of FL in 2D also if there is one. In general perturbation theory has been a reliable guide in the past to charge and spin density wave instabilities and the Cooper instability. This point of view, which has been generally accepted, has recently been called into

question by Anderson[1992] who claims that perturbation theory is not valid for many-body systems, at least in 2D. However we do not address this issue here and calculate corrections to the leading behavior of a 2D FL in perturbation theory.

In 3D the specific heat is known to have a T^3 lnT correction which comes from the ${\xi_p}^3 ln\xi_p$ correction to the self-energy, $\Sigma(p,\xi_p)$, where $\xi_p = (p - p_F)v_F$, p_F is the Fermi momentum, and $v_F = p_F/m$ is the Fermi velocity. In the 1D system the breakdown of the FL can be seen already in the 2nd order perturbation theory where the specific heat correction is given by $\delta C_V \simeq \Gamma_{1D}$ T lnT. In the 2D case we find that $C_V \simeq \gamma$ T + Γ_{2D} T^2 +... where part of the T^2 term comes from a non-analytic correction to the self-energy of the form $sgn(\xi_p){\xi_p}^2$.

In order to compare the properties of FLs in 2D and 3D we first calculate the single-particle self-energy to second order in perturbation theory at zero temperature using the paramagnon model.[Doniach, 1968] For a 3D FL Blaizot and Friman [1981] found

$$Im\Sigma(\vec{p},\epsilon) = \frac{\pi I^2}{8v_F{}^2 p_F{}^2} sgn(\epsilon)([q_c v_F - |\xi_p|]\epsilon^2 + \frac{1}{3}|\epsilon|^3 + ...), \qquad (1)$$

The real part of $\Sigma(\vec{p},\xi_p)$, determined from the Kramers-Kronig relation, is

$$Re\Sigma(\vec{p},\xi_p) = A_{3D}\xi_p + B_{3D}{\xi_p}^3 \ln|\xi_p| + .. \qquad (2)$$

The ${\xi_p}^3 ln|\xi_p|$ term comes from the $|\epsilon|^3$ term in $\mathrm{Im}\Sigma(\vec{p},\epsilon)$ and so it is determined by the long wavelength scattering. For a 2D FL we find

$$Im\Sigma(\vec{p},\epsilon) = sgn(\epsilon)\frac{4I^2}{2\pi N(0)v_F^2}\Big[(\xi_p{}^2 + 2\xi_p(\epsilon - \xi_p))ln(max[\xi_p,|\epsilon|])\Theta(q_c v_F - |\epsilon|)$$
$$+ (\epsilon - \xi_p)^2 ln(|\epsilon - \xi_p|)\Theta(q_c v_F - |\epsilon - \xi_p|) + ..\Big]. \qquad (3)$$

for $\xi_p = 0$. This reduces to the well known results of Hodges et al.[1971] and Bloom[1975] for $\mathrm{Im}\Sigma(\vec{p},\epsilon = \xi_p)$. $\mathrm{Re}\Sigma(\vec{p},\xi_p)$ is

$$Re\Sigma(\vec{p},\xi_p) = A_{2D}\xi_p + B_{2D}sgn(\xi_p){\xi_p}^2 + ... \qquad (4)$$

Here we are concerned with the corrections to the linear terms in ξ_p. Both B_{3D} and B_{2D} are determined by long wavelength scattering. Comparing the corrections to the effective mass terms in $\mathrm{Re}\Sigma(\vec{p},\xi_p)$ in 2D and 3D, one sees that in 2D the correction is non analytic and comes from the leading ϵ dependence of $\mathrm{Im}\Sigma(p,\epsilon)$ whereas in 3D the correction is analytic but comes from non analytic terms in $\mathrm{Im}\Sigma(p,\epsilon)$. This difference between the leading corrections to the linear ξ_p dependence in 2D and 3D is due solely to the different phase space. In contrast to 1D, there is no indication of a breakdown of FL theory in 2D to this order

in perturbation theory. We now consider the thermodynamics of a 2D FL and compare the results with 3D.
Using the RPA approximation the change in the quasiparticle contribution to the entropy due to interactions is

$$\Delta S_{qp} = \gamma_{2D}' T + \Gamma_{2D} T^2 + O(T^3) \tag{5}$$

$$\begin{aligned} \gamma_{2D}' &= \frac{\pi}{6T_F}(A_s + A_a)\frac{q_c}{p_F} \\ \Gamma_{2D} &= \frac{\pi n}{4T_F^2}\sum_\lambda \nu_\lambda (A_\lambda + \int_0^1 du f_\lambda(u)) \end{aligned} \tag{6}$$

where

$$f_\lambda(u) = \frac{[A_\lambda u - tan^{-1}(\frac{A_\lambda u}{1-u^2})]}{u^3},$$

where λ=s or a, ν_s=1, ν_a=3, and

$$A_s = \frac{I}{1+I}, A_a = \frac{-I}{1-I} \tag{7}$$

A_s and A_a are the scattering amplitudes in the symmetric(density) and antisymmetric(spin) channels, n is the density of particles, and $T_F = v_F p_F/2$. The T^2 term in ΔS_{qp} comes from the non-analytic term in $\mathrm{Re}\Sigma(p', \xi_p)$.
Carrying out the calculations in 3D one finds that

$$\Delta S_{qp} = \gamma_{3D}' T + \Gamma_{3D} T^3 lnT + O(T^3) \tag{8}$$

These $T^3 lnT$ terms in 3D are the analog of the T^2 terms in 2D. A difference between 2D and 3D is that Γ_{2D} depends on the scattering amplitudes to all orders whereas Γ_{3D} involves only the second and third powers of the scattering amplitudes.
The collective mode contribution in 2D is $\propto T^2$ so that unlike 3D, where the contribution from collective mode is $\propto T^3$, the correction to the leading temperature dependence in the entropy is not solely from the quasiparticle renormalization. Collecting the quasiparticle and collective mode contributions to the entropy one sees that ΔS is a power series in temperature in 2D. in particular there are no $\ln T$ terms in ΔS which implies that, at least to leading order, quasiparticle damping effects do not contribute to thermodynamic properties in this approximation where the propagators are unrenormalised. Lifetime effects may be estimated using an expression derived by Carneiro and Pethick[1977] in their treatment of the thermodynamics of a FL using fully renormalised propagators. An overestimate for this expression, equation (23) of their paper[Carneiro 1977], gives the contribution to the entropy associated with finite quasiparticle lifetimes on the entropy $\approx T^2 ln^3 T$. This is higher order in temperature than the T^2 corrections found above and are much less important in thermodynamics than a calculation of $\Sigma(p', \epsilon)$ would suggest

Since we have used a particle-hole expansion in the symmetric and antisymmetric channels our results may be easily extended to Landau's Fermi liquid theory by considering Eq.(1) to describe quasiparticles with an effective mass interacting via an effective interaction $f(\vec{p},\vec{p}')$ which can be decomposed into two channels, $f_s(\vec{p},\vec{p}')$ and $f_a(\vec{p},\vec{p}')$. This effective interaction is a long wavelength limit of the particle-hole irreducible four-point vertex and so describes long wavelength properties. This leads to somewhat more complicated expressions when V_s and V_a are substituted for by $f_s(\vec{p},\vec{p}')$ and $f_a(\vec{p},\vec{p}')$. The Landau functions are functions of the variable $s = \frac{\omega}{qv_F}$ and may be expressed as coefficients in a series of Legendre polynomials in which s is the argument. These coefficients are the Landau parameters. The coefficients of the non-analytic terms in $\Sigma(p,\xi_p)$ and their contribution to the T^2 in the entropy can be expressed in terms of Landau parameters as was done in 3D.[Pethick, 1973]
In conclusion there is no evidence that long wavelength interactions between fermions, which give the leading corrections in 3D, lead to a breakdown of FL in 2D. These effects point to the breakdown of FL in 1D. We find that the corrections to the leading linear dependence in $\Sigma(p,\xi_p)$ and C_v for 2D and 3D FL's are very similar.

The authors would like to thank C. J. Pethick for several important contributions to this work. DC acknowledges the support of the Center for Materials Science through the Program in Correlated Electron Theory. This work was supported by the US Department of Energy.

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