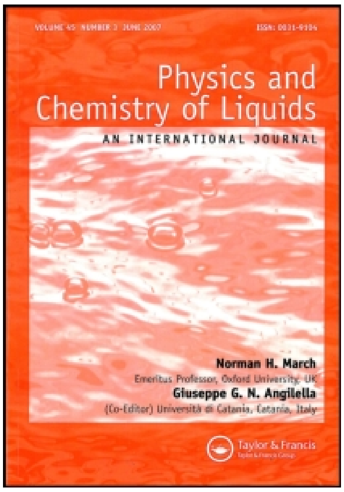

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LETTER

Limit of Fermi Liquid Regime and Binding Energy of Charged (2e) Boson in High T_c Cuprates

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Two-dimensional Fermi liquid theory applied to the normal state of high T_c cuprate materials predicts that the product of electrical resistivity and nuclear spin-lattice relaxation time should be proportional to temperature. This is vindicated for underdoped $YBa_2Cu_4O_8$ above a certain crossover temperature. This latter temperature is then used to estimate the binding energy of the composite charged (2e) Bosons already present above the critical temperature T_c.

KEY WORDS: Fermi liquid, real-space charged Bosons.

Before the discovery of the high T_c cuprates, Nozières and Schmitt-Rink[1] had discussed Bose condensation in a Fermi liquid with attractive interactions; the coupling strength being varied from the weak coupling BCS regime, in which Cooper pairs form in a spin singlet, $l = 0$, state, to the opposite strong coupling limit, where a bound state of a single pair proves possible. These pairs are composite Bosons, which may therefore exhibit the usual Bose-Einstein condensation.

The purpose of this Letter is to combine these findings[1] with the recent work of Egorov and March[2] on the normal state. These authors have pointed out that two-dimensional Fermi liquid theory, as discussed by Kohno and Yamada[3], relates both electrical resistivity R and nuclear spin-lattice relaxation time T_1 to the magnetic susceptibility $\chi(\mathbf{Q})$, where $\mathbf{Q}$ is the antiferromagnetic wave vector. Specifically[3] one can write

$$R \propto \chi(\mathbf{Q}) T^2 \tag{1}$$

and

$$(TT_1)^{-1} \propto \chi(\mathbf{Q}). \tag{2}$$

Elimination of the susceptibility $\chi(\mathbf{Q})$ from Eq. (1) using Eq. (2) yields[2]

$$RT_1 \propto T \tag{3}$$

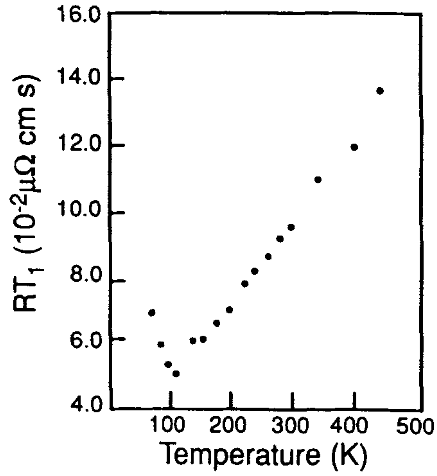

Figure 1 Shows product RT_1 versus temperature T for high T_c material $YBa_2Cu_4O_8$ studied by Bucher *et al.*[4] Plot is constructed purely from experimental data[4] for electrical resistivity R and nuclear spin-lattice relaxation time T_1. Comparison is to be made with prediction (3) of two-dimensional Fermi liquid theory[2]. Fermi liquid regime is evident for $T \gtrsim 150$ K, but crossover to a different lower temperature phase is apparently at $T \sim 100$ K.

in the Fermi liquid regime of the normal state of the high T_c materials. In Figure 1, the plot[2] of RT_1 versus T for the normal state of $YBa_2Cu_4O_8$ using experimental data from Bucher *et al.*[4] is reproduced. It is quite clear from Figure 1 that, while there is indeed a Fermi liquid regime in this material for temperature $T \gtrsim 150$ K in which the prediction (3) is evidently correct, as the temperature in the normal state is lowered a crossover occurs to a different, lower temperature phase.

Returning now to the predictions of Nozières and Schmitt-Rink[1], although these workers were dominantly concerned with predicting the variation of the critical temperature T_c as a function of the coupling strength of the attractive interaction between Fermions, they stressed that one would still anticipate composite Bosons, in the strong coupling regime, in the normal state. Using this argument, it becomes clear from Figure 1 that the temperature, T_m say, corresponding to the minimum of the RT_1 versus T plot, is a direct measure of the binding energy, E_b say, of the composite (2e) Boson. This is to be contrasted with the extreme strong-coupling result for the critical temperature T_c, which becomes insensitive to the coupling strength; a quite different situation from that which obtains in the weak-coupling BCS theory.

Therefore, we propose that as the temperature is lowered in the normal state from $T > T_m$ to $T \sim T_m$, the binding energy E_b of the charged Bosons is such that a concentration, c_b say, of dimers (2e Bosons) is in thermal equilibrium which monomers (dressed Fermions). This equilibrium at temperature T has to accord with the Law of Mass Action, which in turn yields $c_b = c_b(E_b, T)$. It is then clear that, to obtain departures as in Figure 1 from the Fermi liquid regime of monomers, one must have

$$E_b \sim k_B T_m. \tag{4}$$

Since T_m in Figure 1 is ~ 100 K, it then follows that $E_b \simeq 0.01$ eV in the high-T_c material under consideration. Such a crossover from a Fermi liquid regime for $T > T_m$ to a mixed state of (2e) composite Bosons plus Fermion monomers for $T \lesssim T_m$ will naturally have implications for other transport properties than electrical resistivity R; eg Hall coefficient and thermoelectric power[5]. Indeed, crossover behaviour in the same temperature range as in Figure 1 is also apparent there.

Though we are able, from the limit of the Fermi liquid regime obeying Eq. (3), to obtain the binding energy of the composite Boson, we have presently little to add specifically to the question as to the mechanism of the attractive interaction leading to dimer formation[6], nor indeed to the precise nature of the Boson pair. Candidates for the latter real-space pairs remain numerous; eg bipolarons, bisolitons, lone-pairs etc. Nevertheless, it is important in the present context to recall the conclusion of Nozières and Schmitt-Rink[1] that a bound pair with a finite momentum is a collective mode of the superfluid ground state. It then follows that the critical temperature T_c for superconductivity results from thermal excitation of collective modes. This is in complete contrast to the weak coupling superconductors, where the critical temperature results from thermal excitation of individual particles. Unfortunately, thermal excitation of collective modes cannot be treated correctly by mean field theories which include pairing only via an average, static, order parameter. Because of this major obstacle to the calculation of T_c, it is the more important that the characteristic temperature T_m ($> T_c$) in Figure 1 is directly related to the (2e) Boson pair binding energy E_b via Eq. (4). In this context, it does seem of interest to enquire whether any of the presently available models would lead to Boson binding energies in approximate accord with the physical estimate made in Eq. (4).

Therefore, before concluding, passing reference will to made to just one of the candidates for the Boson pair, namely the bisoliton model of high T_c superconductors. In this model, the bisoliton binding energy $\Delta E = 2E_s(0) - E_{bs}(0)$, which in the difference between twice the soliton energy at rest $E_s(0)$ and the bisoliton value $E_{bs}(0)$, is related to the dimensionless nonlinearity parameter g and to the nearest-neighbour exchange integral J through the relation

$$\Delta E = \tfrac{1}{2} g^2 J. \tag{5}$$

This model has been employed by Brizhik *et al.*[8] to study the variation of T_c with pressure and hole concentration for $YBa_2Cu_3O_x$ and $(La_{1-x}M_x)_2CuO_4$. From this work it turns out that $g \simeq 2$ while J is $\sim 10^{-2}$ eV. By using these estimates in Eq. (5), we obtain ΔE as of the same order of magnitude as E_b above. However, we must urge caution here for two reasons: (i) the estimated values of g and J were obtained, as indicated above, by fitting properties of the superconducting state, and (ii) a quasi one-dimensional model was employed.

In summary, experimental data for the product RT_1 versus T for the high T_c material $YBa_2Cu_4O_8$ vindicates Fermi liquid theory based on Eq. (3) above a temperature $T \sim 150$ K. But a clear limit of this Fermi liquid regime is given by the temperature T_m corresponding to the pronounced minimum in Figure 1, which heralds a crossover to a different phase in the normal state. The theoretical work of Nozières and Schmitt-Rink[1] makes it clear that this different phase contains real-space composite Bosons in the normal state, which are precursors to the transition at T_c to the superconducting phase. However, whereas T_c is insensitive to the composite Boson binding energy E_b in the strong coupling regime[1], the temperature T_m at the minimum of Figure 1 is physically a direct measure of E_b/k_B through Eq. (4).

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