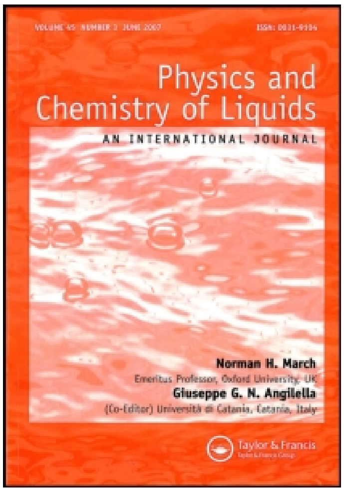

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Letter

IS THE ASYMPTOTIC SCENARIO OF PRECURSOR r SPACE BOSONS CONSISTENT WITH OBSERVATION FOR ELECTRON (HOLE) LIQUIDS IN UNDERDOPED HIGH-T_c CUPRATES?

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The motivation for this study is the review by Timusk and Statt [Rep. Prog. Phys. **62**, 61 (1999)] on the pseudogap in high-temperature superconductors. Here, we confront the experimental data they present, plus that of Norman *et al.* [Nature **392**, 157 (1998)] on the Fermi surface in underdoped high-T_c materials with the theoretical asymptotic scenario of precursor **r** space Boson formation. This reveals no inconsistencies with available observations concerning electron (hole) liquids flowing through such underdoped cuprates with their antiferromagnetic spin fluctuations.

Keywords: Fermi liquid; high-temperature superconductivity; pseudogap regime; real-space charged Bosons

In earlier work [1–3], a two-dimensional Fermi liquid theory prediction for electron (hole) liquids flowing through assemblies with

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antiferromagnetic spin fluctuations, namely:

$$\rho_a T_1 \propto T, \tag{1}$$

where ρ_a and T_1 are respectively electrical resistivity and nuclear spin-lattice relaxation time of ^{63}Cu nuclei, and T is absolute temperature, has been confronted with experiment for underdoped $YBa_2Cu_4O_8$ (Ref. 4). For the material considered, with critical temperature $T_c \sim$ 80 K, the prediction Eq. (1) was well fulfilled above $T \sim 100$ K, but marked deviations occurred in the range down to T_c. These were taken [1 – 3] to be fingerprints of the formation of precursor **r** space Bosons, anticipated in the work of Nozières and SCHMITT-RINK [5] before the discovery of high-T_c superconductors by Bednorz and Müller [6].

Quite recently, the review by Timusk and Statt [7] has appeared on the pseudogap in high-temperature superconductors. They conclude by listing three factors supporting the idea of performed pairs, and then they write, and we quote from them, '*these factors are consistent with the existence of performed pairs, of some description. They need not be real space pairs and could just be dynamic correlations. Although the evidence so far is consistent with preformed pairs, it does not prove their existence*'.

It is this review [7], and in particular the above quote from it, that has motivated us to reopen the issues focussed on in Refs. [1 – 3]. We raise below some matters which we believe are central to the formation (or otherwise) of precursor **r** space Bosons in underdoped high-T_c cuprates, to which we restrict our attention through the present study. Highly relevant matters, in our opinion, are then as follows:

(i) How will the Fermi surface before the (assumed) formation of **r** space Bosons (below 100 K in Ref. [1]) be depleted by monomer electrons (holes) being sucked out of the carrier liquid by the binding of $2e$ Bosons?

(ii) What properties will reflect the increase of the **r** space Boson concentration before the superconducting temperature T_c is reached?

(iii) Can other theories than Fermi liquid predict the result Eq. (1) pointed out by Egorov and March [1]? For instance, can the much used t-J model in the present context predict Eq. (1) at a suitable temperature above T_c in an underdoped cuprate, as required by experiment?

(iv) Does the number of adjacent CuO_2 layers in the compounds under discussion affect the validity of the prediction Eq. (1) in any significant way?
(v) Does the *d*-wave symmetry of the order parameter enter the picture based on the asymptotic scenario of **r** space Boson formation?

and finally

(vi) Does the Wiedemann-Franz relation contain information relevant to establishing a precursor **r** space Boson picture as a useful viewpoint?

In the ensuing discussion, we take point (i) to (vi) in turn, and present, (qualitative, rather than quantitative) arguments in each case.

Concerning (i) above, it is clear that precursor **r** space Boson formation, if it occurs, must extract carriers from the Fermi surface. Thus, even though the emphasis throughout is on the **r** space Boson asymptotic scenario, there must be a quite intimate link with that constant energy surface in **k** space characterizing the Fermi energy. And naturally, such **k** space features must involve the Boson concentration, increasing as T_c is approached from above. Chiofalo *et al.* [8] have presented models of the **r** space Boson concentration as a function of T above the critical temperature T_c: we shall return to their work below. It is tempting to assume that Figure 1e of Norman *et al.* [9] on the destruction of the Fermi surface in underdoped high-T_c superconductors already reflects the reduction of **r** space Boson concentration as the temperature T is increased well above $T_c \sim 85\,\mathrm{K}$ for underdoped $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Ref. [9]). This latter observation has already taken us well into issue (ii) raised above.

Turning to issue (iii), it would seem of considerable interest for theory, and for subsequent experimental work, to compare and contrast the prediction Eq. (1) of two-dimensional Fermi liquid theory, which is in agreement with experiment for the sample considered in Ref. [4] when T is substantially above T_c, with that of crucially different models. Thus, the much-supported *t-J* model by numerous theoretical groups must be shown to also yield Eq. (1) as a high temperature limit, *if* it is to remain a viable approach to high-T_c behaviour underdoped cuprates. Issue (iv) is also related to Eq. (1). In the language of the pseudogap favoured by Timusk and Statt [7] in their experimental review, '*there appears to be no strong connection*

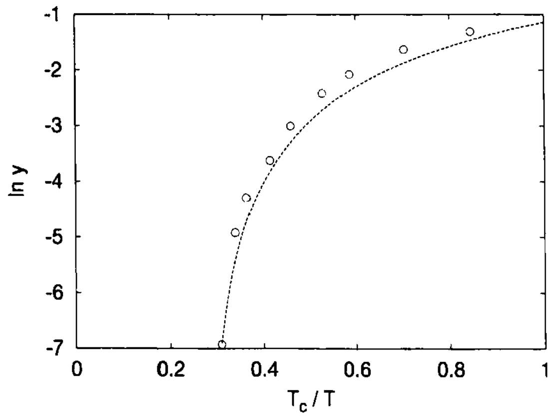

FIGURE 1 Natural logarithm of the dimensionless quantity $y = 1 - (\rho_a/\rho_a^{T \gg T_c})^{1/2}$ plotted *versus* T_c/T from Bucher *et al.* [4] experimental data for underdoped $YBa_2Cu_4O_8$, above the critical temperature $T_c \sim 80$ K. The dashed line is a guide to the eye. In the precursor **r** space Boson picture, we anticipate that the quantity y will be intimately connected with the Boson concentration. The Arrhenius plot has a shape which is compared with a Boson-Fermion model in Figure 2.

between the presence of a pseudogap and the number of adjacent CuO_2 layers in the compound'. This is, of course, in contrast to the behaviour of T_c itself, which is established as connected with the number of adjacent layers.

Point (v) needs a good deal of study before a firm conclusion can be established. We think that it must involve an intimate connection between the (predominantly *d*-wave) symmetry of the order parameter and the wave function of the **r** space Bosons. We refer the reader, in this context, to the brief discussion in Appendix B of the review article by Scalapino [10].

Alexandrov and Mott [11] have already discussed the Wiedemann-Franz law in the context of the bipolaron superconductivity, which has been challenged, quite generally, as a mechanism for high-T_c cuprates by Ranninger *et al.* [12]. These workers [11] give in a high temperature limit a bosonic (*b*) Lorenz number

$$L_b = \frac{1}{2}\left(\frac{k_B}{e}\right)^2 \tag{2}$$

which is considerably smaller than the electronic value, L_e, namely

$$\frac{L_b}{L_e} = \frac{3}{2\pi^2}. \tag{3}$$

However, in the present model, in marked contrast to the discussion of Alexandrov and Mott [11], the contribution of the Bosons with twice the electronic charge must be weighted by the Boson concentration (see Figs. 1 – 2). The common ground, however, with Alexandrov and Mott [11], is that it remains to understand the ratio of the in-plane electrical resistivity ρ_a to the measured thermal conductivity. Presently, however, we can discern no irreconcilable difficulty for the precursor **r** space Boson viewpoint.

Having taken the six issues in turn above, let us return to the result, Eq. (1). Else-where [13], by focussing on the in-plane resistivity ρ_a, we have demonstrated, by a proposed phenomenological generalization of Fermi liquid theory, taken through what is termed often the pseudogap region, that the correct generalization of Eq. (1) is

$$\rho_a^2 T_1 = (a + bT)(c + dT), \tag{4}$$

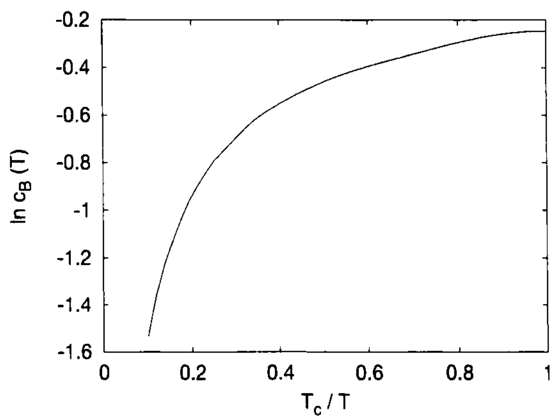

FIGURE 2 Boson concentration in the normal state taken from the mixture model of Chiofalo *et al.* [8], with an interaction parameter $g = 15$ defined in that reference. The shapes of Figures 1 and 2 are clearly similar, though detailed comparison is inappropriate as the Boson concentration $c_B(T)$ is here for an isotropic three-dimensional model.

where $bT + a \equiv \rho_a^{T \gg T_c}$ and $dT + c \equiv (\rho_a T_1)^{T \gg T_c}$ should be a read as high temperature expansions for ρ_a and $\rho_a T_1$, respectively. What seems remarkable about the generalization Eq. (4) is that, for all temperatures $T > T_c$, Eq. (4) represents the data of Bucher *et al.* [4] on $YBa_2Cu_4O_8$ using information on the right-hand side, which has knowledge only of high temperature properties. In other words, pseudogap information does not appear in the combination $\rho_a^2 T_1$ in Eq. (4).

The burden of what follows is to demonstrate, on the contrary, that ρ_a and T_1 separately have clear fingerprints individually of the 'pseudogap' regime, and we shall present arguments that these fingerprints are not inconsistent with the precursor **r** space Boson scenario.

To approach this, we use the Boson-Fermion mixture of Chiofalo *et al.* [8], in combination with the electrical resistivity formula of Rousseau *et al.* [14], which was originally set up for liquid metals with completely degenerate electrons. This formula is of force–force correlation function type and involves the square of $(\partial\gamma(\mathbf{r}_1, \mathbf{r}_2, E)/\partial E)_{E_F}$, where E_F is the Fermi energy. If we represent the density matrix γ of the above mixture model, with Boson concentration $c_B(T)$ in the normal state, as

$$\gamma_{\text{mixture}}(\mathbf{r}_1, \mathbf{r}_2, E) = [1 - c_B(T)]\gamma_{\text{Fermion}} + c_B(T)\gamma_{\text{Boson}}, \qquad (5)$$

then we reach the approximate prediction that $c_B(T)$ is intimately related to the dimensionless quantity $y = 1 - (\rho_a/\rho_c^{T \gg T_c})^{1/2}$. Therefore, in Figure 1 we have plotted the experimental data of Bucher *et al.* [4] in this form. Of course, we can only make a qualitative comparison of the factual data in Figure 1 with the model Chiofalo *et al.* [8]. Since this model has a Boson binding energy E_B, but plus an interaction term denoted by g in their work, we have taken data on $c_B(T)$ for $T > T_c$ from their Figure 7, and have plotted this as ln $c_B(T)$ *vs.* T_c/T in Figure 2. We restrict ourselves to the qualitative point that Figures 1 and 2 have quite similar shapes. However, we must caution that Figure 1 is about two-dimensional CuO_2 planes, whereas Figure 2 is for an isotropic three-dimensional model of a Boson-Fermion mixture.

The point made in Eq. (4) that $\rho_a^2 T_1$, as demonstrated elsewhere [13], does not contain knowledge beyond high temperature information, prompts us to stress again that ρ_a and $\rho_a T_1$ separately have valuable content as to 'mechanism' in the pseudogap region (compare Figs. 1 and 2).

As a final observation in this same context, Eq. (1) came, as noted by Egorov and March [1], by elimination of the susceptibility $\chi(\mathbf{Q})$ at he antiferromagnetic wave-vector $\mathbf{Q}$ from [15]

$$\rho_a \propto T^2 \chi(\mathbf{Q}), \tag{6}$$

and

$$(TT_1)^{-1} \propto \chi(\mathbf{Q}). \tag{7}$$

Evidently, to reach Eq. (4), we must effect generalizations of these two equations. Equation (7) can, in fact, be written in terms of a dynamical wavevector ($\mathbf{q}$) and frequency (ω) dependent susceptibility, and we shall summarize this, after an integration, in the formal statement

$$(TT_1)^{-1} \propto \chi_D(\mathbf{Q}). \tag{8}$$

But ρ_a is 'directional' and we shall rewrite Eq. (6) as

$$\rho_a \propto T^2 \chi_a(\mathbf{Q}). \tag{9}$$

We assume that $\chi_a(\mathbf{Q})$ and $\chi_D(\mathbf{Q})$ somehow reflect anisotropy in the high-T_c underdoped cuprate connected with the antiferromagnetic fluctuations, but must become equal for $T \gg T_c$. Also χ_a^2 is related approximately to χ_D by Eq. (4) for T. But a specific model will, of course, be needed eventually for these 'generalized susceptibilities' consistent with the experimental data of Bucher *et al.* [4].

In summary, the present study has raised six issues in connection with the question posed in the title of the present article. It is, in our opinion, encouraging that, at the present time, there is no irreconcilable inconsistency between the asymptotic scenario of precursor $\mathbf{r}$ space Boson formation and available experimental observations in underdoped cuprates. We feel it is important to emphasize the restriction to underdoped materials, and that a different type of physical mechanism may well be required for optimal and overdoping.

Acknowledgment

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