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Nodal Quasiparticles versus Phase Fluctuations in High T_c Superconductors: An Intermediate Scenario

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We explore a BCS Bose Einstein crossover scenario for $0 \leq T \leq T_c$ and its implications for the superfluid density and specific heat. The low lying excitations consist of nodal (fermionic) quasi-particles as well as excited (bosonic) pair states. Semi-quantitative comparison with cuprate data is reasonable, with no compelling indications for Landau parameter effects.

1. Introduction

Within the pseudogap regime of the cuprates, it has been widely argued that the excitations of the superconducting state are predominantly fermionic[1] or predominantly bosonic[2] in character. We have pointed out[3] that there is a third scenario which is no less likely and which, at the least, needs to be considered on an equal footing. This third scenario emerges when one studies the BCS Bose-Einstein condensation (BEC) crossover picture for $0 \leq T \leq T_c$. At weak coupling (when the coherence length ξ is large) the excitations are dominantly fermionic, and at very strong coupling (small ξ) they are dominantly bosonic. At intermediate coupling, which is likely to be appropriate to the cuprates, the excitations are of mixed character. In this paper we discuss the implications of this third scenario, in the context of semi-quantitative comparisons with experiment, for the superfluid density and specific heat.

There have been a number of recent papers which have presented similar comparisons within the context of the " fermionic" or nodal quasi-particle picture, extended, however, to a Fermi liquid based interpretation[4–7]. This differs conceptually from the original formulation of Lee and Wen[1] because the important Mott insulator constraint ($\omega_p^2 \approx x$) is enforced via a hole concentration (x) dependent Landau parameter F_1^s which then constrains the penetration depth $\lambda(x)$ via $d\lambda^{-2}/dT \approx x^2$. These x dependences are considerably different from those of the spin-charge separation approach[1] which is based on the presumption that $d\lambda^{-2}/dT$ is x independent.

An underlying philosophy of the present paper is that fundamental features of the pseudogap phase should be accommodated at the outset, before including Landau parameter effects. Our viewpoint is different from the phenomenology of Lee and Wen[1] because here T_c is associated with *both* nodal quasiparticles and bosonic pair excitations. Stated alternatively, in the BCS-BEC crossover picture there is an important distinction between the order parameter Δ_{sc} and excitation gap Δ at *all* temperatures.

This approach leads to a new mean field-like theory[3] which incorporates (i) the usual BCS equation for $\Delta(T)$ and for (ii) the chemical potential $\mu(T)$, along with a third new equation for (iii) $\Delta^2 - \Delta_{sc}^2$ which is related to the number of thermally excited pair (bosonic) excitations. The first two equations enforce an underlying fermionic constraint so that the bosons of the strong coupling limit *are different* from those of a true boson system, such as He^4. To include the Mott insulator constraint the Fermi velocity v_F must then be x-dependent, as shown in Figure 1a (along with experimental data), in a way which *directly* reflects the x-dependence of $\lambda(T=0) = \lambda_o$, shown in the inset to Figure 1c. Here the parameters were chosen to give a reasonable fit to the measured phase diagram for the YBaCuO system[3].

2. Penetration Depth and Specific Heat

In order to calculate the penetration depth and specific heat within the present approach, the fermionic contributions must be quantified, just as in the nodal quasi-particle picture. This contribution is accompanied by an additive bosonic component[3,8]. So as not to complicate the logic, we compute the former, by taking the second velocity contribution[1] v_2 as given by a perfect d-wave model; thus the x depen-

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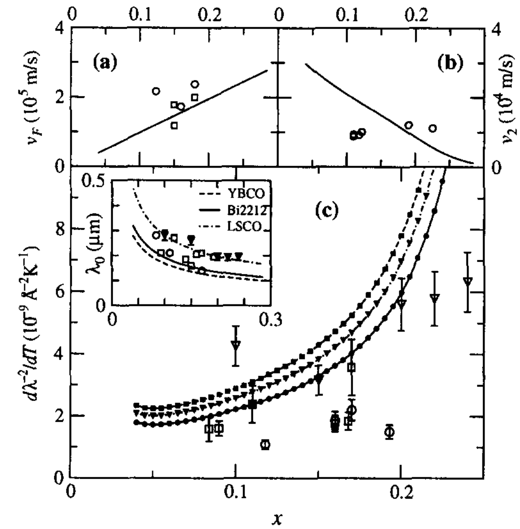

Figure 1. Input parameters (1a,1b) to $d\lambda^{-2}/dT$ plotted in 1c, for various cuprates indicated by the legend in Fig. 2a. Inset in 1c shows λ_0 vs doping x. Data on v_2 from Ref. [5], v_F from (○) Refs. [9–12] (□)[1,13], others (○, Bi2212) Refs. [11,12]; (□, YBCO) [14,15]; (▿, LSCO) [16].

dence of v_2 entirely reflects that of $\Delta(x)$, as shown in Fig. 1b, which is in slight disagreement with the data indicated in 1b[5]. The resulting values for the inverse squared penetration depth are plotted in Fig. 1c, along with a collection of experimental data. The predicted increase at large x is a reflection of the behavior of $\Delta(x)$. Given the spread in the data for all quantities indicated in Fig. 1, it would appear that there are no obvious inconsistencies.

In Fig. 2 we show the x dependent coefficient of the quadratic term (2a) in the specific heat $C_v = \gamma^* T + \alpha T^2$, along with the linear term (2b). The first of these reflects the fermionic quasi-particle contribution (which depends on v_2 and v_F) and the second derives purely from the bosonic contribution. Also indicated are a collection of experimental data on three different cuprates. We know of no other intrinsic origin for this γ^* term, which despite its widespread presence is usually attributed to extrinsic effects.

The upturn at large x in the γ^* data, is of no concern, since it is a reflection of the normal state behavior (shown more completely in the inset). For overdoped samples, at the lowest $T_c \approx 0$, extrinsic,e.g., paramagnetic impurity, effects make it difficult to observe α and γ^* in the intrinsic superconducting state.

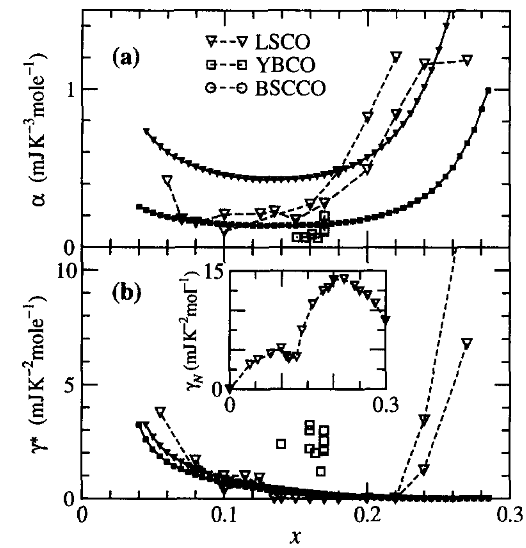

Figure 2. Quadratic (2a) and linear (2b) T contributions to C_v in various cuprates. Data are from (▿) Refs. [17,18] and (□) Refs. [19–22]. Inset in 2b shows normal state result from Ref. [18]. Compare open (experiment) with corresponding filled (theory) symbols. (per mol of formula units)

REFERENCES

1. P.A. Lee & X.-G. Wen, Phys. Rev. Lett. **78**,4111(1997).
2. V.J. Emery & S.A. Kivelson, Nature **374**, 434 (1995).
3. Q.J. Chen, I. Kosztin, B. Janko, & K. Levin, Phys. Rev. Lett. **81**, 4708 (1998).
4. A.J. Millis *et al.*, J. Phys. Chem. Solids **59**,1742(1998).
5. J. Mesot *et al.*, Phys. Rev. Lett. **83**, 840 (1999).
6. M. Chiao *et al.*, cond-mat/9910367.
7. T. Xiang and C. Panagopoulos, cond-mat/9910098.
8. Q.J. Chen, I. Kosztin, & K. Levin, cond-mat/9908362.
9. T. Valla *et al.*, Science **285**, 2110 (1999).
10. X.J. Zhou, private communications (data on v_F).
11. O. Waldmann *et al.*, Phys. Rev. B **53**, 11825 (1996).
12. S.-F. Lee *et al.*, Phys. Rev. Lett. **77**, 735 (1996).
13. K. Krishana *et al.*, Phys. Rev. Lett. **75**, 3529 (1995).
14. D.A. Bonn *et al.*, Czech J. Phys. **46**, 3195 (1996).
15. C. Panagopoulos *et al.*, Phys. Rev. B **57**, 13422 (1998).
16. C. Panagopoulos *et al.*, Phys. Rev. B **60**, 14617 (1999).
17. J.W. Loram *et al.*, Proc. 10th Ann HTS workshop, (World Scientific, Singapore, 1996), p. 341.
18. N. Momono *et al.*, Physica C **233**, 395 (1994).
19. K.A. Moler *et al.*, Phys. Rev. B **55**, 3954 (1997).
20. A. Junod *et al.*, Proceedings of LT22 (Helsinki, 1999).
21. D.A. Wright *et al.*, Phys. Rev. Lett. **82**, 1550 (1999).
22. R.A. Fisher *et al.*, Physica C **252**, 237 (1995).