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Reconciliation of normal-state and superconductive specific-heat, optical, tunneling, and transport data on Y-Ba-Cu-O

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Quantum percolation theory reconciles a variety of data on $YBa_2Cu_3O_{7-\delta}$, and in particular explains the linear temperature dependence of planar resistivity in the normal state.

All high-T_c cuprate superconductors lie close to metal-insulator transitions, which has led me to introduce a quantum percolation model of their electronic properties.[1,2] In this model interlayer defects provide electrical bridges which render CuO_2 layers metallic and superconductive. In the absence of such bridges even doped layers are assumed to be insulating because of topological constraints imposed by disorder.[3,4]

Until recently detailed analysis of experimental data using this model was difficult because of the extrinsic effects produced by inhomogeneities in oxygen concentration[5] or by minority magnetic phases.[6,7] I now believe that enough reproducible data exist to justify the present analysis, which separates intrinsic electrical effects in a consistent way and in particular explains the famous linear temperature dependence of the planar resistivity in the normal state.[8-10]

My discussion is focused on spectroscopic experiments which reveal the presence of states below the superconductive gap E_g of Y-Ba-Cu-O, which lies near 460 cm^{-1}, especially high-resolution Raman data.[11-13] The orthorhombic differences[13] between the scattering strength $I(x,x)$ and $I(y,y)$ in the normal state from an untwinned single crystal provide evidence for the involvement of CuO chains in the CuO_2 interplanar bridges, as discussed elsewhere.[14] Here for brevity I concentrate on the salient feature of the data,[11] which is the constancy of the planar scattering strength $2\ I_\parallel = I(x,x)+I(y,y)$ in the normal state and its proportionality to $\Delta E = E - E_F$ in the superconductive state below E_g.

A full theory of the ΔE dependence of the Raman scattering strength per state in these marginal conductors could be quite complex. Instead of doing such modeling one can compare the Raman data with tunneling data, because tunneling into superconductive metals has provided good replicas of quasiparticle densities of states.[15] Reproducible tunneling characteristics have been obtained from chemically etched Y-Ba-Cu-O surfaces.[16] These show a gap consistent with the Raman data and a large excess or leakage current below the gap. The problem is to obtain a functional form for this excess current which is consistent with the Raman data, and then to interpret this functional form in the context of quantum percolation.

The interpretation of the tunneling conductance σ is complicated by the presence of an extrinsic contribution σ_s which peaks near $E_g/5$ and which is probably associated with steps.[16] I consider two possible $\Delta E \to 0$ extrapolations of the bulk conductance $\sigma_b = \sigma - \sigma_s$: $\sigma_b = a + bV$, with $a = 0$ or $a \neq 0$. Consider first $a \neq 0$. Then $S_\parallel$, the Raman scattering strength per state, must be $S_\parallel(\Delta E) = s\Delta E$ to explain $I_\parallel(\Delta E)$ in the superconductive state. But now in the normal state to explain the constancy of $I_\parallel(\Delta E)$, one must have $N(\Delta E) = c(\Delta E)^{-1}$, a divergent density of electronic states which yields a divergent normal-state electronic specific heat, which I take to be unacceptable. Thus $a = 0$, and $S_\parallel(\Delta E) = s$, which means that the Raman data on the cuprates yields faithful replicas of the quasiparticle density of states near E_F.

Quantum percolation theory separates the density of electronic states near E_F, $N(E)$, into localized and extended parts,[3,4] $N(\Delta E) = N_l(\Delta E) + N_e(\Delta E)$, and only the extended states become superconductive. Thus from the Raman data $N_l(\Delta E) = c\Delta E$, while $N_e(\Delta E)$ is nearly constant. In normal metals with a high density of defects the electrical resistivity is constant at low temperatures T (residual resistivity). In percolative cuprates, however, for an extended state to carry current it must be phase coherent between adjacent CuO_2 planes. Defect scattering destroys this phase coherence, and so we expect that defect scattering will always scatter extended states (e) into localized states (l). This scattering rate is proportional to ΔE because $N_l(\Delta E)$ is proportional to ΔE. In normal metals, by contrast, this scattering rate is constant. This means that the temperature-independent residual resistivity of normal metals is replaced by a linear temperature dependence, which is the striking charac-

teristic of all layered cuprates, even $Bi_2(Bi,Sr)CuO_6$, where the resistivity is linear[17] from $T=7$ to 700 K.

Here, I have outlined a plausible model of the electronic structure of high-T_c cuprates. Apart from its close relationship to the phenomenology of these materials (proximity to a metal-insulator transition, essential rôle of layering), the strongest evidence for this model comes at present from specific chemical evidence for interlayer bridges. This evidence is obtained from analysis of specific Raman-active vibrational modes[18] and from the composition dependence of superconductivity in $Nd_{2-x}Ce_xCuO_{4-y}$ alloys.[14] It should be mentioned that throughout this analysis I assume that the primary mechanism responsible for the high T_c's of these materials is giant electron-phonon interactions at interlayer and intralayer defects which pin E_F.

In discussing their own data Klein and co-workers have developed a model[19] of a "highly correlated electron liquid" which is similar in some ways to the present model. However, quantum percolation theory replaces the phrase "highly correlated" with a specific topological mechanism based on marginal dimensionality.[2-4] The theory finds specific support in the identification of interlayer electrical bridges[14,18] in Y-Ba-Cu-O and $Nd_{2-x}Ce_xCuO_{4-y}$ which play a rôle here analogous to that of intervalley scattering in degenerate semiconductors.[20] While these analogies are interesting, the material-specific properties of layered cuprates can be explained much more incisively by quantum percolation theory.

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