On the character of the superconductor to metal transition in overdoped cuprates

"Dependence of the critical temperature in overdoped copper oxides on superfluid density," I. Bozovic, X. He, J. Wu, and A. T. Bollinger, Nature (2016).

Recommended with a commentary by Steven A. Kivelson, Stanford

This newly published paper by Bozovic *et al* systematically explores the nature of the superconducting state as a function of doped hole concentration, p, in a series of high quality films of the cuprate high temperature superconductor, LSCO, as p approaches the critical doping, p_c, at which the superconducting transition temperature, $T_c(p)$, vanishes. Since for $p > p_c$, the ground-state appears to be metallic (*i.e.* the resistivity approaches a finite value as $T \to 0$), p_c is a superconductor-to-metal quantum critical point (QCP). Specifically, Bozovic *et al* have quantitatively measured the p and T dependences of the superfluid stiffness, $\kappa(p, T)$, for all $T < T_c(p)$.

One of the most fruitful strategies for exposing the essential physics of any phase of matter is to study the nature of the continuous transitions from it to a nearby "normal" state. That in a conventional BCS superconductor, the thermal transition is well understood in terms of a mean-field theory based on the Cooper instability reflects much that is essential both about the superconducting phase and about the normal metallic phase from which it originates. In the cuprates, unambiguous inferences from the thermal transitions have been difficult to make, given that the normal state is either a mysterious "bad metal" or an even more mysterious pseudo-gap state. Recently, a number of remarkable experiments on underdoped cuprates which probe the zero-temperature (quantum) evolution from the superconducting to a metallic phase in a high magnetic field have been the catalyst for a number of new insights. (Here, "underdoped means $p < p_{opt}$ where p_{opt} is the value of p at which $T_c(p)$ reaches its maximum value, and "overdoped means $p > p_{opt}$.) However, until now, there has been relatively little reliable and quantitative data on the doping driven transition in overdoped curpates.

The salient observations in Bozovic *et al* are:

- **1a)** The ground-state superfluid stiffness, $\kappa(T = 0)$, decreases continuously with increasing p such that $\kappa \to 0$ as $p \to p_c$. In terms of magnitude, if one expresses the $T = 0$ superfluid stiffness per plane,

κ_{2d}, in units of temperature, one finds that κ_{2d} is comparable (within a factor of order 1) to T_c.

- **1b)** Specifically, as $T_c(p)$ decreases from 40K to 10K there is an approximately linear relation between κ_{2d} and T_c of the form $T_c \approx T_0 + \alpha\ \kappa_{2d}$, where $T_0 \approx 7K$ and $\alpha \approx 0.4$. However, still nearer to p_c, T_c drops abruptly with a new power-law, $T_c \approx [T_1\ \kappa_{2d}]^{1/2}$ where $T_1 \approx 16K$.

- **2)** Even for films with the lowest T_c's, κ is a linear function of T down to temperatures well below T_c. Linear in T dependence of κ is a well documented feature of a superconductor with gap nodes in the "superclean" limit, where the quasiparticle scattering rate, $\hbar/\tau$, is small compared to the temperature, *i.e.* $\hbar/\tau \ll T \ll T_c$. For a clean superconductor (*i.e.* one in which $\hbar/\tau \ll kT_c$) the famous Ferrel-Glover-Tinkham sum rule implies that κ_{2d} is equal to the Drude weight, independent of the magnitude of T_c.

- **3)** The relevance of the clean limit was corroborated in several ways. A comparison was made between the T dependences of two films with comparable values of T_c, one purposely disordered with 0.5% Zn substitution for Cu. In the Zn doped sample, $\kappa(T)$ has a roughly quadratic T dependence for $T < T_c/2$. More directly, from the magnitude of the resistivities ($\rho \sim 10\mu\Omega$-cm) just above T_c, one can get an estimate of the mean-free path of $\ell \sim 10^2$nm, which is long compared to any reasonable estimate of ξ_0. The resistive transitions are all sharp, which can be taken as evidence against any large-scale inhomogeneities. Moreover, while the magnitudes of the measured resistivities in the present films appear to be slightly lower than those measured in crystals[1] in the same range of doping, the general trends are quite similar, supporting the conclusion that the results are intrinsic to overdoped LSCO.

The results of Bozovic *et al* are difficult to reconcile with the widely held expectation that the physics of highly overdoped cuprates is more or less the conventional physics of a BCS-like superconductor to metal transition. This can be seen by by "proof by contradiction." Assume overdoped LSCO could be accurately described in terms of a normal state with weakly interacting Fermi liquid quasiparticles and BCS superconductivity. In BCS theory, a superconductor-to-metal transition occurs where the effective pairing interaction, $\lambda - \mu^\star$, changes sign from positive on the superconducting side to negative on the metallic side. In the clean limit, $\kappa(T=0)$ would jump discontinuously across the transition, although in reality, since ξ_0 diverges as $p \to p_c^-$, close enough to criticality, there would be a crossover to the "dirty limit" where $\kappa(T=0) \sim \kappa_{clean}(\tau/\hbar)T_c$. Moreover, the divergence of ξ_0 means that the Ginzburg-criterion would be satisfied everywhere except exponentially close to T_c, *i.e.* conventional analysis would suggest that fluctuation effects would be negligible near p_c. (By contrast, as emphasized by Bozovic *et al*, the fact that $\kappa_{2d} \sim T_c$ means that phase fluctuations of the superconducting order parameter are an order one effect.)

Thus, the most basic question raised by the present data is what accounts for the singular decrease of the superfuid density as $p \to p_c$? 1) It could reflect singular behavior of an unspecified "normal state" over a range of p up to p_c. The observation in Ref. [1] that in crystals of LSCO in the same range of doping, the low T resistivity measured at high enough magnetic fields to quench superconductivity exhibits strange (linear in T) temperature dependence with a coefiscient that vanishes as $p \to p_c^-$ certainly supports this circle of ideas. However, it is unclear what normal-state QCP would occur with nearly the same p_c as the superconductor-to metal QCP. 2) It could be that the answer lies in some sort of two-fluid description of the normal state, in which one component condenses below T_c while the other forms an incoherent metal (of some sort).

In the future, a study of the optical conductivity of these same films in the terahertz regime[2] could provide valuable information concerning the origin of the spectral weight that condenses to form the superconducting condensate. In the mean time, what could be better than crisp experiments that reveal simple and clearly significant systematics, but whose correct interpretation is unknown?

References

[1] R.A. Cooper, Y. Wang, B. Vignolle, *et al*, Science **323**, 603-607 (2009).

[2] Such data exists for lower dopings: L.S. Bilbro, R. V. Aguilar, G. Logvenov, *et al*, Nature Physics **7**, 298 (2011).