Superfluid density reveals a quantum critical point between d-wave superconductivity and a Mott insulator

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Recommended and a commentary by Catherine Kallin, McMaster University

Understanding the low doping regime of the cuprate superconductors is widely believed to hold the key to understanding high temperature superconductivity. It is here that the Mott insulating phase gives way to d-wave superconductivity, with the anomalous pseudogap phase sandwiched in between at finite temperatures. Much recent attention has focused on the pseudogap phase since it connects to both of these interesting phases and is robust over a wide range of doping and temperature. However, the very low temperature, low doping regime, which most directly connects the Mott insulating phase to the superconducting phase has largely remained elusive, with its extreme sensitivity to disorder and what some have argued is an intrinsic tendency to inhomogeneity. It is in this regime that various inhomogeneous and spin-glass phases have been found in some of the cuprate materials.

This paper reports on some surprising experimental results on strongly underdoped, ultraclean single crystals of YBCO. Broun *et al.* have assembled a set of three physical measurements exploiting the new technique of tuning the hole doping of YBCO by allowing oxygen in the CuO chain layer to anneal over time. This technique allows for substantial changes of hole doping in a single sample without any change in cation disorder or other systematic errors associated with doping a series of different samples.

They measure the c-axis and a-b plane penetration depths (or superfluid densities) and the lower critical field H_{c1} in samples with T_c's as low as 4K. The superconducting transition at larger dopings has been found to be in the 3D-XY universality class, and one would expect this to cross over to 2D behaviour since penetration depth measurements show the layers are becoming more weakly coupled with decreasing doping. However, Broun *et al.* see no sign of 2D critical behaviour and, in fact, the transition at these low dopings is found to be mean-field like. Also the Uemera scaling, where T_c varies linearly with superfluid density as is observed over large parts of the phase diagram of many cuprates, is found to give way to a sublinear relation at these low dopings. The authors conclude that the observed mean field behaviour is a consequence of entering the regime where 3D-XY has crossed over to (3+z)D-XY fluctuations, where z is the dynamical critical exponent. In other words, they argue that these experimental results can be understood as resulting from close proximity to a quantum critical point separating the superconducting phase from an insulating phase. The sublinear relation between the superfluid that the H_{c1} measurements yield a small coherence length, even as T_c approaches zero, which is also consistent with a large domain for critical fluctuations.

The experimental results are surprising in that one might have expected to see some evidence of 2D critical behaviour and the mean-field behaviour is seen over a fairly substantial range of T_c's. However, the results are consistent with those for YBCO films and the interpretation as a strongly paired superconductor disordering due to phase fluctuations in the vicinity of a quantum critical point appears simple and compelling in many ways. [See M. Franz and A.P. Iyengar, Phys. Rev. Lett. **96**, 047007 (2006) for comparison to 4D-XY calculations, which include the effect of d-wave nodal quasiparticles.] This work sheds new light on this important but elusive part of the cuprate phase diagram and should stimulate further experimental and theoretical investigations of this regime. In particular, one needs to measure the antiferromagnetic phase boundary at low temperatures in similar crystals and to add the role of fluctuating magnetism to this picture. In doing so, we may learn whether inhomogeneous phases are playing a role even in these ultraclean YBCO samples.