Varying temperature in STM studies of the cuprates

Visualizing pair formation on the atomic scale in the high-T_c superconductor $Bi_2Sr_2CaCu_2O_{8+\delta}$, K. K. Gomes, A. N. Pasupathy, A. Pushp, S. Ono, Y. Ando and A. Yazdani

http;//arXiv:0706.0214

Nature **447**, 569 (2007).

Imaging the Two Gaps of the High-T_c Superconductor Pb-$Bi_2Sr_2CuO_{6+x}$, M. C. Boyer, W. D. Wise, K. Chatterjee, M. Yi, T. Kondo, T. Takeuchi, H. Ikuta, and E. W. Hudson

http://arXiv:0705.1731.

Recommended with a Commentary by Subir Sachdev, Harvard University

Much experimental and theoretical attention continues to be showered on analyzing the fascinating 'pseudogap state' of the cuprate superconductors. In the temperature-doping plane, this is the low doping region above the superconducting critical temperature, which does not behave like a conventional Fermi liquid metal. Instead, it exhibits precursors of the superconductor, and possibly other exotic orderings. Theorists are faced here with a strongly coupled problem, comparable in difficulty to that of the quark-gluon plasma, which has resisted description in terms of the excitations of some limiting regime. We do, however, have the benefit of a plethora of experimental probes, and technical advances in their precision continue to produce exciting new physics.

These papers above report one such impressive technical advance: the ability to vary temperature in scanning microscopy studies while maintaining spatial registry at a sub-angstrom resolution. This is a powerful asset in studies of the cuprate superconductors: in principle, it can disentangle the effects of spatial inhomogeneity from changes in carrier concentration or temperature.

In the debate over the pseudogap state it is important, in my opinion, to keep a focus on distinguishable characterizations. A commonly asked question is: Is this state a superconductor with strong phase fluctuations, or is the gap due to some other competing order parameter ? However, "a superconductor with strong quantum phase fluctuations" eventually crosses a quantum phase transition to a non-superconducting state, and if this phase is a conventional insulator, it is required to have spatial modulations (a 'competing order parameter') such that there are an even integer number of electrons per unit cell. So a discussion using sharper characterizations is required.

Here, I will use a very useful characterization proposed most clearly by M. Le Tacon *et al.* (Nature Physics **2**, 537 (2006)), which encapsulates the central mystery of the pseudogap state. Le Tacon *et al.* pointed out that the electronic quasiparticles at different momenta have very different dependencies on doping and temperature. Those near the 'nodal' points (these are points along the diagonals of the Brillouin zone with gapless Bogoliubov quasiparticles in the superconductor) are characterized by an energy scale which tracks the superconducting critical temperature. In contrast, the electrons with momenta near the 'antinodes' (near $(\pi, 0)$ and other symmetry related points in the Brillouin zone) display a broad spectral gap which increases monotonically with descreasing doping.

The present STM experiments provide complementary information in real space, in contrast to the momentum space information of Raman scattering obtained by Le Tacon *et al.* Although there do appear to be important differences between the two STM experiments in their observations and interpretations, the overall picture that emerges is similar to that proposed by Le Tacon *et al.*.

Gomes *et al.* examine a range of doping concentrations in the Bi-2212 superconductor. Near optimal doping, they find a spatially inhomogeneous gap which appears to locally characterize the inhomogeneous evolution of the spectrum as a function of temperature. In the underdoped sample, however, they do find the emergence of a smaller, temperature-independent, energy scale in their spectrum. This is possibly related to the nodal energy scale of Le Tacon *et al.*.

Boyer *et al.* present data on overdoped Bi-2201. However, they argue from previous observations that this material exhibits the pseudogap state even at these doping concentrations, and is ideally suited to separating the distinct energy scales characterizing the electrons. Their essential step is to *divide* the tunneling spectrum by a normalizing spectrum above the critical temperature. After this procedure, they find a small gap in the spectrum which vanishes at the critical temperature. This connection between the tunneling spectrum and the critical temperature is novel and quite remarkable. It is tempting to identify the small gap with the nodal energy scale of Le Tacon *et al.*. However, the temperature dependencies of the small gap reported by the two STM groups are distinct: hopefully future co-ordinated studies by different groups and different probes on the same samples will settle these important issues.