From Fermi Arcs to the Nodal Metal: Scaling of the Pseudogap with Doping and Temperature

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Recommended and a Commentary by Elihu Abrahams, Rutgers University.

Because of major technical advances in energy and momentum resolution during the past decade, angular-resolved photoemission (ARPES) has become a very important technique for investigating the electronic properties of solids. In particular, ARPES studies of the cuprate superconductors have revealed much important information against which theoretical approaches for these high-temperature superconductors must be measured.

In the two-dimensional case, ARPES measures the energy and momentum dependence of the single particle spectral function $A(\mathbf{k},\omega)$. From this, one can find the quasiparticle dispersion and the Fermi surface, i.e. the locus of points in k-space which separates the occupied from the unoccupied states at zero temperature. Among the important ARPES results are the observation of nodes in the superconducting energy gap function, the determination of a pseudogap in the normal state of underdoped cuprates and the evolution of the Fermi surface with doping from underdoped to overdoped.

Kanigel et al have made detailed studies of Fermi surface evolution in six underdoped BSCCO-based samples. In the doping range studied, it is known from earlier measurements that the Fermi surface consists of four almost circular arcs centered on the four equivalent [1,1] "nodal" directions in the Brillouin zone. The k-space regions in which there is no Fermi surface at k_F are the ones having a pseudogap. Kanigel et al study the temperature and doping dependence of the pseudogap and its k-dependence in their samples. Their data strongly suggests that the momentum dependence of the pseudogap is, for all the samples, the same function of T/T^*, where $T^*(x)$, a function of doping x is the temperature below which the pseudogap first appears.

The data also allow the determination of the temperature and doping dependences of the length of the Fermi arcs. The latter expand to a full Fermi surface as T increases through T^*. It is found that for $0.1 < T/T^* < 1$, the length of the Fermi arcs is quite close to a linear function of T/T^*, which, although superconductivity intervenes for these samples, extrapolates to zero, i.e. to four points, as $T/T^* \to 0$.

The important lessons and challenges for theory are the scaling behavior, with $T/T^*(x)$, of the pseudogaps momentum dependence and the nearly linear dependence, with zero intercept, of the Fermi arc length on $T/T^*(x)$. The latter implies that if superconductivity did not intervene, the ground state in the "pseudogap phase" would be a metal whose Fermi surface consists of four points.

Among the questions for experiment, two are of immediate interest: One is, where in the Brillouin zone are the Fermi points located, at $[\pi/2,\pi/2]$ or elsewhere? This can be answered with the ARPES data. A second question, whose answer is not accessible by ARPES, is what is the symmetry of the pseudogap? Although the amplitude of the pseudogap has the same angular dependence as the (d-wave) superconducting gap, at present there is no information about its phase. Both these questions are of importance to those theories that can predict the observed evolution of the Fermi arcs.