CHARGE INHOMOGENEITY AND HIGH TEMPERATURE SUPERCONDUCTIVITY

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When the condensation of a gas of fermions into a (self-bound) liquid state is frustrated by the long-range Coulomb interaction, the consequence is a large local fluctuation of the charge density, together with pairing on a high energy scale. The competition between these two effects at long length scales determines the nature of the ordered state at low temperatures. Evidence for the central role of this competition in determining the physical properties of the high temperature superconductors is provided by the delicate interplay of superconductivity, charge and spin ordering, and structural phase transformations in the La_2CuO_4 family of materials. There the gas-liquid transition corresponds to the phase separation of holes doped into an antiferromagnetic insulator. Because of the low superfluid density and poor conductivity, the critical temperature for the superconducting transition in underdoped and optimally doped materials is governed by the onset of phase coherence and not by the pairing energy scale.

1 Introduction

The fundamental driving force for high temperature superconductivity and for many of the unusual properties of the cuprates is the frustration of the motion of holes in an antiferromagnet. *Neutral holes* are unstable to phase separation into an antiferromagnetically ordered insulating region and a hole-rich metallic region^{1,2}. This is the best compromise between the hole kinetic energy and the exchange interaction between the spins. Since superexchange is itself a kinetic process, phase separation minimizes the total zero-point energy of the strongly-correlated system. *For charged holes* the long-range Coulomb interaction frustrates phase separation, unless the dopants are mobile enough to counterbalance the effect of the long-range Coulomb interaction, as in the case of photodoping or oxygen doping^{3,4}. Of course this does not mean that phase separation is without consequence. Between the spinodals, the instability of the neutral system (which is signalled by a negative compressibility) is converted by the Coulomb interaction into charge inhomogeneity on intermediate time scales or length scales, and especially into ordered or fluctuating charge stripes^{5,6}. As we shall see, the other consequence is local pairing on a high energy scale. Typically, charge ordering and superconducting phase coherence compete at long length scales, although they may coexist in specific regions of the phase diagram⁷.

There is extensive experimental evidence to show that: 1) Phase separation is the fate of neutral holes in an antiferromagnet^{3,4}. 2) The La_2CuO_4 family displays ordered⁸ or fluctuating^{9,10,11} charge stripes together with antiphase spin domains. 3) Charge order and superconductivity compete with each other^{12,13,14}.

The existence of charge-density wave fluctuations adds a new dimension to discussions of the physics of the high temperature superconductors which, almost from the outset, have been dominated by the interplay of antiferromagnetism and superconductivity. The clearest

evidence for this behavior is to be found in the La_2CuO_4 family although, as we shall see, angle resolved photoemission data on other materials may also be understood from this point of view. Nevertheless the three phenomena are simply different manifestations of a common underlying physical theme, and the best way to investigate any one of them is to find the material in which it shows up the most clearly.

The charge stripes are topological defects, which form antiphase domain walls in the antiferromagnetic order of the background spins⁸. We have argued¹⁵ that this kind of “*topological doping*” is a common feature of correlated insulators such as polyacetylene (for which the defects are solitons) and the high temperature superconductors, and that it is responsible for the rapid restoration of the symmetry of the ground state upon doping; non-topological defects would produce much more modest reduction in the magnitude of the order parameter, proportional to the dopant concentration.

2 Evidence for Stripes.

Recent neutron scattering studies⁸ of $\text{La}_{1.6-x}\text{Nd}_{0.4}\text{Sr}_x\text{CuO}_4$ with $x = 0.12$ found a succession of transitions; first to the low temperature tetragonal (LTT) structure, then to a charged-ordered state (charge-stripes) and finally, at a slightly lower temperature, to a period-doubling magnetically-ordered state. We conclude that the transitions are driven by frustrated kinetic phase separation because the charge order appears first and the relatively low charge density along the stripes (one doped hole per two Cu ions) allows the holes to be mobile. The alternative route to stripe order, (a Hartree-Fock, Fermi surface instability¹⁶) predicts a single transition to a charge and spin ordered insulating state, with one doped hole per Cu, twice as large as observed.

$\text{La}_{1.6-x}\text{Nd}_{0.4}\text{Sr}_x\text{CuO}_4$ with $x = 0.12$ does not exhibit bulk superconductivity. But there are substantial low-energy stripe fluctuations in optimally-doped, superconducting samples of $\text{La}_{2-x}\text{Sr}_x\text{CuO}_4$; inelastic neutron scattering experiments^{9,10,11} have found peaks at energies as low as a few meV and in essentially the same positions in k -space as in (ordered) $\text{La}_{1.6-x}\text{Nd}_{0.4}\text{Sr}_x\text{CuO}_4$. Clearly the stripe correlations are an essential part of the physics of these materials.

The single-particle properties of a disordered stripe phase¹⁷ also account for the peculiar features of the electronic structure of high temperature superconductors observed by angle-resolved photoemission spectroscopy (ARPES) on hole-doped high temperature superconductors. In particular, the spectral function of holes moving in a disordered stripe background reproduces the experimentally-observed shape of the Fermi surface and the existence of nearly dispersionless states in its neighborhood. The essential ingredient in this interpretation of the data is a background of slowly-fluctuating stripes whose dynamics is determined by collective effects (the competition between phase separation and the long-range Coulomb force), rather than the single-particle behavior.

3 The Mechanism

As might be expected, an appreciation of the electronic structure and the underlying physics also leads to a natural mechanism of high temperature superconductivity. When the holes on the stripes tunnel into the intervening region, which has a low density of doped holes and strong antiferromagnetic correlations, they experience the very same effective attraction that would have caused them to coalesce (phase separate) in the absence of the longer range Coulomb interaction. In fact, the holes moving on a stripe form a quasi one-dimensional electron gas in an “active” environment which has low-energy excitations in the spin (and possibly charge) degrees of freedom. The environment renormalizes the kinetic energy of the holes and mediates effective interactions between them¹⁸. We have found several such processes that lead to pairing, *even though the basic Hamiltonian contains only repulsive interactions*¹⁸. In particular, when two holes hop into the antiferromagnetic environment, they may form a bound state, which typically has a large binding energy and a low mobility, and cannot, by itself, lead to high temperature superconductivity. However, the holes in the stripe are able to combine this large binding energy with their own mobility and achieve a high superconducting transition temperature¹⁸.

4 Phase Fluctuations

It is possible to define a characteristic temperature for superconducting phase ordering T_θ^{max} which is proportional to the phase stiffness $V_0 = (\hbar c)^2 d / 16 \pi e^2 \lambda^2(0)$ where $\lambda(0)$ is the zero-temperature penetration depth and d is the spacing between the CuO_2 planes. We have shown¹⁹ that, if $T_c \ll T_\theta^{max}$, then phase fluctuations are relatively unimportant and T_c is likely to be close to the mean-field transition temperature T^{MF} predicted by BCS theory. On the other hand, if $T_\theta^{max} \sim T_c$, then the value of T_c is determined primarily by phase ordering, and T^{MF} is simply the characteristic temperature below which local pairing becomes significant.

The value of T_θ^{max}/T_c for the cuprate superconductors is of order unity¹⁹, which places them in a quite different category from conventional superconductors, for which the ratio can be as large as 10^5 . Indeed, T_c is predominantly determined by phase fluctuations in underdoped high temperature superconductors and by the mean-field transition temperature T^{MF} in overdoped materials such as Tl 2201 ($T_\theta^{max}/T_c \geq 2$). Optimally doped materials, such as $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ and $\text{La}_{2-x}\text{Sr}_x\text{CuO}_4$, with δ and x in the neighborhood of 0.05 and 0.15 respectively, are in the crossover region between the two.

When T_c is much smaller than T^{MF} , the existence of pairing without phase coherence should be manifested as a pseudogap in the temperature range $T_c < T < T^{MF}$. Such a pseudogap has been observed in underdoped samples of high temperature superconductors, such as $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ and $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+x}$ and in the stoichiometric material $\text{YBa}_2\text{Cu}_4\text{O}_8$. The pseudogap has been seen in spin²⁰, charge^{21,22,23}, and single-electron²⁴ properties. Moreover, the central peak in the a -axis optical conductivity (which becomes a δ -function in the superconducting state) already narrows above T_c ²⁵ in $\text{YBa}_2\text{Cu}_4\text{O}_8$ and underdoped $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$. The prediction¹⁹ that T_c is suppressed by phase fluctuations in organic conductors has been confirmed by the observation²⁶ of pseudogap behavior in

the nuclear spin relaxation rate. Taken as a whole, these experiments strongly support the existence of a phase fluctuation regime in the cuprate and organic superconductors.

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