Stripes and superconductivity in cuprate superconductors

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ABSTRACT

One type of order that has been observed to compete with superconductivity in cuprates involves alternating charge and antiferromagnetic stripes. Recent neutron scattering studies indicate that the magnetic excitation spectrum of a stripe-ordered sample is very similar to that observed in superconducting samples. In fact, it now appears that there may be a universal magnetic spectrum for the cuprates. One likely implication of this universal spectrum is that stripes of a dynamic form are present in the superconducting samples. On cooling through the superconducting transition temperature, a gap opens in the magnetic spectrum, and the weight lost at low energy piles up above the gap; the transition temperature is correlated with the size of the spin gap. Depending on the magnitude of the spin gap with respect to the magnetic spectrum, the enhanced magnetic scattering at low temperature can be either commensurate or incommensurate. Connections between stripe correlations and superconductivity are discussed.

Keywords: superconductivity, cuprates, stripes

1. INTRODUCTION

The concept of charge stripes\(^1\) is a controversial one in the field of high-temperature superconductivity. There is direct evidence from neutron diffraction measurements for charge and spin stripe order in a couple of cuprates,\(^4,5\) \(\text{La}_{1.6-x}\text{Nd}_{0.4}\text{Sr}_x\text{CuO}_4\) and \(\text{La}_{2-x}\text{Ba}_x\text{CuO}_4\) with \(x \approx \frac{1}{8}\); however, the ordering of stripes is correlated with the depression of the superconducting transition temperature, \(T_c\).\(^6\) (For reference, Fig. 1 shows examples of possible stripe domains.) While it is clear that static ordering of stripes competes with superconductivity, this does not mean that dynamic stripes are necessarily bad for superconductivity. In this paper, I will argue the case that stripes, in fact, underlie the high-temperature superconductivity in under- to optimally-doped cuprates (with the implication that stripes, or more general forms of charge inhomogeneity, are essential to the superconductivity).

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**Figure 1.** Cartoon of two equivalent domains of stripe order in \(\text{CuO}_2\) planes: (a) vertical stripes, (b) horizontal stripes. Only Cu sites are indicated, with arrows indicating ordered magnetic moments and circles indicating hole-rich charge stripes. The absolute phase of the stripe order with respect to the lattice has not been established by experiment, so stripes could also be centered on Cu sites, rather than on bonds.
2. STRIPE ORDER IS COMMON

As a starting point to understanding the cuprates, it makes sense to consider the behavior of related compounds. Consider the systems La$_{2-x}$Sr$_x$M$O_4$, where, of course, the compounds with $M = $ Cu are superconducting for $0.05 < x < 0.25$. For $M = $ Ni, Co, and Mn, the trend is to have either charge and locally-antiferromagnetic spin order, or else a metallic ferromagnetic state. In the case of $M= $ Ni, diagonal charge and spin stripes are observed over the range $0.2 < x < 0.5$, with checkerboard order at $x = 0.5$; dynamic stripe-like spin correlations survive in the disordered state of La$_{2-x}$Sr$_x$NiO$_4$. A state close to checkerboard order is also observed for $M = $ Co and $x = 0.5$. When $M = $ Mn and $x = 0.5$, the presence of several degenerate, partially-filled $d$ levels leads to a complicated phase at low temperature involving charge, orbital, and spin ordering. The ferromagnetic metallic state is observed in pseudo-cubic manganese perovskites.

The point here is that there is a common tendency in layered transition-metal oxides for the holes doped into the two-dimensional (2D) antiferromagnetic planes to segregate, order, and coexist with locally antiferromagnetic domains. In three-dimensional perovskites, metallic behavior tends to be coupled with ferromagnetism. Thus, the cuprates are surprising not only for their superconductivity, but also for their metallic normal state with antiferromagnetic spin excitations. Nevertheless, in seeking to understand these properties, it should not be surprising, given the context, that charge segregation effects may be relevant.

3. UNIVERSAL MAGNETIC EXCITATION SPECTRUM

Considerable progress has been made in the last couple of years in characterizing the magnetic excitation spectra of superconducting cuprates with inelastic neutron scattering. In the case of YBa$_2$Cu$_3$O$_{6.4}$, it has become clear that, besides the so-called “resonance” peak, there are also excitations that disperse upwards to higher energies and downwards to lower energies. A similar “hour-glass” dispersion is found over a range of $x$, from 0.5 to 0.95. A very similar dispersion has also been observed in La$_{1.875}$Ba$_{0.125}$CuO$_4$ (LBCO) and in optimally-doped La$_{2-x}$Sr$_x$CuO$_4$; a plot of the dispersion for LBCO is shown in Fig. 2. As the LBCO sample exhibits stripe order, it is natural to interpret the magnetic excitations as spin waves of the ordered configuration. It turns out that the dispersion is not consistent with linear spin-wave theory, in that we do not observe symmetric dispersion (and intensity) about the incommensurate ordering wave vectors. (In contrast, linear spin-wave theory gives a good description of the spin excitations in diagonally stripe-ordered La$_{2-x}$Sr$_x$NiO$_4$.)

Another way to think about the spectrum is to take into account that bond-centered stripes at $x = \frac{1}{2}$ define two-leg spin ladders (see Fig. 1). The dispersion of triplet excitations within an isolated ladder, with $J = 100$ meV is shown by the solid line in Fig. 2; it agrees with the measurements surprisingly well. To account for the downward dispersion, one must allow for a coupling between the ladders (across the charge stripes). An alternative approach, involving calculating excitations with respect to a particular mean-field stripe state, also gives good agreement with the data. In contrast, it is not possible to reproduce the full spectrum with a model based on checkerboard order.

While the simple spin-only models do remarkably well, they have shortcomings. In particular, they do not properly describe the anisotropic magnetic scattering measured in a detwinned sample of YBa$_2$Cu$_3$O$_{6.85}$ by Hinkov et al. Of course, that sample has no static stripe order. The results may be compatible with dynamic stripes.

In LBCO, the magnetic spectrum at low energies ($< 12$ meV) is not very sensitive to the presence of stripe order, although the frequency dependence of the scattered intensity is. Measurements are underway to check for temperature dependence at energies up to 100 meV. The similarities of the excitations in the ordered and disordered states suggests that the stripe correlations survive in a dynamic form in the disordered state. The similarities among the different cuprate families further suggest that dynamic stripes are common in these materials and coexist with superconductivity.

In optimally-doped superconducting samples, an energy gap appears in the magnetic excitations for temperatures below $T_c$. The measurements of Christensen et al. on La$_{1.84}$Sr$_{0.16}$CuO$_4$ indicate that the weight below the spin gap is shifted to energies just above the spin gap. In this particular case, where the spin gap is small ($\sim 8$ meV, depending on how one measures it) compared to the saddle-point energy of the dispersion, the enhanced intensity below $T_c$ all occurs at incommensurate wave vectors (see Fig. 3). Applying a magnetic field tends to
Figure 2. Symbols: experimentally measured dispersion\(^{22}\) of magnetic excitations along \(Q = (0.5 + q, 0.5, l)\) in stripe-ordered La\(_{1.875}\)Ba\(_{0.125}\)CuO\(_4\). The solid line is the calculated\(^{28}\) dispersion along a two-leg ladder with \(J = 100\) meV.

shift some of this intensity back into the gap.\(^{34, 35}\) In compounds such as YBa\(_2\)Cu\(_3\)O\(_{6+x}\) and Bi\(_2\)Sr\(_2\)CaCu\(_2\)O\(_{8+\delta}\), where the spin gap is much larger and closer to the saddle-point energy, much of the transferred scattering weight below \(T_c\) appears at the saddle point, yielding the commensurate resonance.\(^ {17, 36, 37}\) The saddle point energy (at optimum doping) appears to scale with the superexchange energy (which is somewhat larger in La\(_2\)CuO\(_4\) than in YBa\(_2\)Cu\(_3\)O\(_6\)). The spin-gap energy varies substantially among different cuprate families, and shows a correlation with \(T_c\), as indicated in Fig. 3. The idea that a universal magnetic spectrum plus a spin gap might explain various observations in the cuprates was first suggested by Batista \textit{et al.}\(^ {38}\)

4. STRIPES AND SUPERCONDUCTIVITY

I have argued that the magnetic excitation spectrum observed in the cuprates is associated with stripe correlations. If this is correct, and if magnetic correlations are important to the mechanism of superconductivity, then it appears that dynamic stripes may not only underlie the superconductivity in the hole-doped cuprates, but also be an essential component of the superconductivity. One proposed mechanism for the superconductivity, the spin-gap proximity effect,\(^ {39}\) is based on this sort of picture. The correlation between \(T_c\) and spin gap energy shown in Fig. 3 is predicted by this approach.\(^ {40}\) In fact, it has been argued that charge inhomogeneity is essential to obtaining high-temperature superconductivity.\(^ {41}\)

There are, of course, limits to the stripe picture. We know from the work of Yamada \textit{et al.}\(^ {42, 43}\) on LSCO that the magnetic incommensurability, which is inversely proportional to the stripe spacing, increases linearly from \(x = 0.02\) to about 0.13, saturating beyond that point (see top panel of Fig. 4). (Similar behavior has been reported for YBCO,\(^ {36}\) although it appeared to saturate at a smaller incommensurability. This is due to the fact that the incommensurability was measured at about 30 meV, and did not take into account the dispersion of the excitations to larger wave vectors at lower energies.) In the saturated region, where the charge stripes are separated by about 4 lattice spacings, it seems unlikely that added holes would be forced into the existing stripes,
increasing the hole density per stripe. It seems more likely that that the added holes will form uniformly-doped regions, so that, with increasing $x$, the fractional area occupied by stripes at any point in time will decrease. This is indicated schematically in the middle panel of Fig. 4.

Wakimoto et al.\textsuperscript{45} have recently shown that the low-energy ($\sim 6$ meV) magnetic scattering decreases rapidly with overdoping beyond $x \sim 0.2$, going to zero by $x = 0.30$. In the stripe picture, the magnetic excitations are associated with the stripe-correlated regions, so that the experimental results are consistent with a decrease in the stripe fraction in the overdoped regime. Measurements are currently underway to test whether this decrease in magnetic signal also applies at higher energies, up to 100 meV.

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Figure 4. Top: schematic diagram of magnetic incommensurability (elastic or low-energy inelastic) measured in La$_{2-x}$Sr$_x$CuO$_4$ by neutron scattering as a function of doping. Middle: schematic diagram suggesting regions of existence and coexistence of various electronic states; from left, antiferromagnetic order, diagonal stripes, vertical stripes, uniformly-doped phase. Bottom: typical curve of $T_c$ vs. doping.

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