Experimental Evidence for Topological Doping in the Cuprates

J. M. Tranquada

Physics Department, Brookhaven National Laboratory, Upton, NY 11973-5000

Abstract. Some recent experiments that provide support for the concept of topological doping in cuprate superconductors are discussed. Consistent with the idea of charge segregation, it is argued that the scattering associated with the “resonance” peak found in YBa$_2$Cu$_3$O$_{6+x}$ and Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ comes from the Cu spins and not from the doped holes.

INTRODUCTION

One of the striking features of the layered cuprates is the coexistence of local antiferromagnetism with homogeneous superconductivity. After recognizing that the superconductivity is obtained by doping holes into an antiferromagnetic (AF) insulator, the simplest way to understand the survival of the correlations is in terms of spatial segregation of the doped holes [1]. If the segregated holes form periodic stripes, then time-reversal symmetry requires that the phases of the intervening AF domains shift by $\pi$ on crossing a charge stripe [2–4]. This topological effect is quite efficient at destroying commensurate AF order without eliminating local antiferromagnetism [5].

The clearest evidence for stripe correlations has been provided by neutron and x-ray scattering studies of Nd-doped La$_{2-x}$Sr$_x$CuO$_4$. Much of this work, together with related phenomena in hole-doped nickelates, has been reviewed recently [6,7] and some further details are given in [8–10]. In the Nd-doped system, the maximum magnetic stripe ordering temperature corresponds to an anomalous minimum in the superconducting $T_c$. This fact has caused some people to argue that stripes are a special type of order, unique to certain cuprates, that competes with superconductivity. However, there has been a significant number of recent papers that provide experimental evidence for stripe correlations in other cuprates. Some of these are briefly discussed in the next section.

One corollary of the stripe picture is that the dynamic spin susceptibility measured by neutron scattering and nuclear magnetic resonance (NMR) comes dominantly from the Cu spins in instantaneously-defined AF domains and not directly from the doped holes. This has implications for the interpretation of features such
as the “resonance” peak found in YBa$_2$Cu$_3$O$_{6+x}$. Some discussion of this issue is presented in the last section.

**EVIDENCE SUPPORTING STRIPES**

In La$_{2-x}$Sr$_x$CuO$_4$, long-range AF order is destroyed at $x \geq 0.02$; however, a recent muon-spin-rotation ($\mu$SR) study by Niedermayer et al. [11] (presented at this conference) shows that the change in local magnetic order is much more gradual. At $T \leq 1$ K, the average local hyperfine field remains unchanged even as LRO disappears, and it decreases only gradually as $x$ increases to $\sim 0.07$. In particular, local magnetic order is observed to coexist with bulk superconductivity.

In contrast, Wakimoto et al. [12] have shown, using neutron scattering, that the static spatial correlations change dramatically as $x$ passes through 0.05. The magnetic scattering near the AF wave vector is commensurate for $x \leq 0.04$, and incommensurate for $x \geq 0.06$, consistent with stripes running parallel to the Cu-O-Cu bonds. The scattering is also incommensurate at $x=0.05$, but with the peaks rotated by 45° compared to the case for $x \geq 0.06$, suggesting the presence of diagonal stripes, as in La$_{2-x}$Sr$_x$NiO$_4$ [6].

Local magnetic inhomogeneity at $x = 0.06$, consistent with a stripe glass, is confirmed by a $^{63}$Cu and $^{139}$La NMR/NQR study by Julien et al. [13]. One particularly striking observation is a splitting of the $^{139}$La NMR peak for $T < 100$ K, in a manner very similar to that observed below the charge-stripe–ordering temperature in La$_{1.67}$Sr$_{0.33}$NiO$_4$ [14]. Another feature noticed by Julien et al. [13] is a loss of $^{63}$Cu NQR intensity at low temperature. Independently, Hunt et al. [15] have investigated this intensity anomaly in a number of systems, including Nd- and Eu-doped La$_{2-x}$Sr$_x$CuO$_4$, and shown that the intensity loss correlates with the charge-stripe order parameter observed by neutron and x-ray diffraction [6]. Their results imply that static charge-stripe order occurs in La$_{2-x}$Sr$_x$CuO$_4$ for $x \leq 0.12$. This result is quite compatible with recent neutron-scattering work that shows static incommensurate magnetic order at $x = 0.12$ ($T \leq 31$ K) and $x = 0.10$ ($T \leq 17$ K), but not at $x = 0.14$ [16].

Static stripes are not restricted to Sr-doped La$_2$CuO$_4$. Lee et al. [17] have demonstrated that incommensurate magnetic order occurs, with an onset very close to $T_c$ (42 K), in an oxygen-doped sample with a net hole concentration of $\sim 0.15$. Furthermore, the $Q$ dependence of the magnetically-scattered neutron intensity indicates interlayer spin correlations very similar to those found in undoped La$_2$CuO$_4$, thus showing a clear connection with the AF insulator state.

Stripe spacing, which is inversely proportional to the incommensurability, varies with doping. Yamada et al. [18] have shown that, for a number of doped La$_2$CuO$_4$ systems with hole concentrations up to $\sim 0.15$, $T_c$ is proportional to the incommensurability. Recently, Balatsky and Bourges [19] have found a similar relationship in YBa$_2$Cu$_3$O$_{6+x}$, in which the incommensurability is replaced by the $Q$ width of the magnetic scattering about the AF wave vector. Indications that the magnetic
scattering might be incommensurate were noted some time ago [20,21]; however, it is only recently that Mook and collaborators [22,23] have definitively demonstrated that there is a truly incommensurate component to the magnetic scattering in underdoped \( \text{YBa}_2\text{Cu}_3\text{O}_{6+x} \). They have also shown that the modulation wave vector is essentially the same as in \( \text{La}_{2-x}\text{Sr}_x\text{CuO}_4 \) with the same hole concentration.

As discussed by Mook [24] and by Bourges [25], there is also a commensurate component to the magnetic scattering in \( \text{YBa}_2\text{Cu}_3\text{O}_{6+x} \). This component, which sharpens in energy below \( T_c \), is commonly referred to as the “resonance” peak. It has now been observed in an optimally doped crystal of \( \text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta} \) by Fong et al. [26]. This observation demonstrates a commonality, at least among the double-layer cuprates studied so far. Of course, the significance of the resonance peak itself depends on the microscopic source of the signal, and this is the topic of the next section.

**MAGNETIC SCATTERING COMES FROM COPPER SPINS**

Comparisons of the spin-fluctuation spectra in un- and optimally-doped \( \text{La}_{2-x}\text{Sr}_x\text{CuO}_4 \) [27] and in un- and under-doped \( \text{YBa}_2\text{Cu}_3\text{O}_{6+x} \) [28–30] show that, although doping causes substantial redistributions of spectral weight as a function of frequency, the integrated spectral weight (over the measured energy range of 0 to \( \sim 200 \) meV) changes relatively little. The limited change in spectral weight is most easily understood if the magnetic scattering in the doped samples comes from the Cu spins in magnetic domains defined by the spatially segregated holes.

The spin fluctuations in \( \text{YBa}_2\text{Cu}_3\text{O}_{6.5} \) look very similar to overdamped spin waves [29]. With increasing \( x \), the spin fluctuations measured at low temperature gradually evolve into a peak that is sharp in energy [24,31]. The intensity of this resonance peak has a well defined dependence on the component of the scattering wave vector perpendicular to the CuO\(_2\) planes, \( Q_z \). If \( d_\perp \) is the spacing between Cu atoms in nearest-neighbor layers, then

\[
I(Q_z) \sim \sin^2(\frac{1}{2}Q_zd_\perp).
\]  

(It should be noted that the spacing between oxygen atoms in neighboring planes is significantly different from the Cu spacing, and is incompatible with the observed modulation [20].) It so happens that this response is precisely what one would get for Cu spin singlets formed between the layers [32]. Thus, both the evolution of the resonance peak with doping and the \( Q_z \) dependence of its intensity suggest that the scattering is coming from antiferromagnetically coupled Cu spins.

Is commensurate scattering compatible with stripe correlations? In order to observe incommensurate peaks, it is necessary that there be interference in the scattered beam between contributions from neighboring antiphase magnetic domains. If the spin-spin correlation length along the modulation direction becomes
smaller than the width of two domains, then the scattering from the neighboring domains becomes incoherent, and one observes a broad, commensurate scattering peak. To the extent that singlet correlations form within an individual magnetic domain, the coupling between domains will be frustrated. If the charge stripes in nearest neighbor layers align with each other, then the magnetic domains will also be aligned, and the magnetic coupling between them should enhance singlet correlations. Thus, the weak interlayer magnetic coupling in bilayer systems may enhance commensurate scattering and the spin gap relative to the incommensurate scattering that dominates at low energies in $\text{La}_{2-x}\text{Sr}_x\text{CuO}_4$.

If the resonance peak is associated with the spin fluctuations in itinerant magnetic domains, then it is not directly associated with the superconducting holes. Instead, it corresponds to the response of the magnetic domains to the hole pairing. The temperature and doping dependence of the resonance peak indicates that the Cu spin correlations are quite sensitive to the hole pairing.

ACKNOWLEDGMENTS

While I have benefited from interactions with many colleagues, I would especially like to acknowledge frequent stimulating discussions with V. J. Emery and S. A. Kivelson. Work at Brookhaven is supported by the Division of Materials Sciences, U.S. Department of Energy under contract No. DE-AC02-98CH10886.

REFERENCES

1. V. J. Emery and S. A. Kivelson, this proceeding; cond-mat/9902077.
2. O. Zachar, S. A. Kivelson, and V. J. Emery, Phys. Rev. B 57, 1422 (1998).
3. J. Zaanen and O. Gunnarsson, Phys. Rev. B 40, 7391 (1989).
4. S. R. White and D. J. Scalapino, Phys. Rev. Lett. 80, 1272 (1998).
5. A. H. Castro Neto and D. Hone, Phys. Rev. Lett. 76, 2165 (1996).
6. J. M. Tranquada, in Neutron Scattering in Layered Copper-Oxide Superconductors, edited by A. Furrer (Kluwer Academic, Dordrecht, 1998), pp. 225–260.
7. J. M. Tranquada, J. Phys. Chem. Solids 59, 2150 (1998).
8. J. M. Tranquada, N. Ichikawa, and S. Uchida, cond-mat/9810212.
9. J. M. Tranquada, N. Ichikawa, K. Kakurai, and S. Uchida, J. Phys. Chem. Solids (in press); cond-mat/9903453.
10. N. Ichikawa, Ph.D. thesis, University of Tokyo.
11. C. Niedermayer, C. Bernhard, T. Blasius, A. Golnik, A. Moodenbaugh, and J. I. Budnick, Phys. Rev. Lett. 80, 3843 (1998).
12. S. Wakimoto, R. J. Birgeneau, Y. Endoh, P. M. Gehring, K. Hirota, M. A. Kastner, S. H. Lee, Y. S. Lee, G. Shirane, S. Ueki, and K. Yamada, cond-mat/9902201.
13. M.-H. Julien, F. Borsa, P. Carretta, M. Horvatić, C. Berthier, and C. T. Lin, cond-mat/9903005.
14. Y. Yoshinari, P. C. Hammel, and S.-W. Cheong, cond-mat/9804219.
15. A. W. Hunt, P. M. Singer, K. R. Thurber, and T. Imai, cond-mat/9902348.
16. G. Aeppli, T. E. Mason, S. M. Hayden, H. A. Mook, and J. Kulda, Science 278, 1432 (1997).
17. Y. S. Lee, R. J. Birgeneau, M. A. Kastner, Y. Endoh, S. Wakimoto, K. Yamada, R. W. Erwin, S.-H. Lee, and G. Shirane, cond-mat/9902157.
18. K. Yamamoto, T. Katsufuji, T. Tanabe, and Y. Tokura, Phys. Rev. Lett. 80, 1493 (1998).
19. A. V. Balatsky and P. Bourges, cond-mat/9901294.
20. J. M. Tranquada, P. M. Gehring, G. Shirane, S. Shamoto, and M. Sato, Phys. Rev. B 46, 5561 (1992).
21. B. J. Sternlieb, J. M. Tranquada, G. Shirane, M. Sato, and S. Shamoto, Phys. Rev. B 50, 12915 (1994).
22. H. A. Mook, P. Dai, S. M. Hayden, G. Aeppli, T. G. Perring, and F. Doğan, Nature 395, 580 (1998).
23. P. Dai, H. A. Mook, and F. Doğan, Phys. Rev. Lett. 80, 1738 (1998).
24. H. A. Mook, this proceeding.
25. P. Bourges, this proceeding; cond-mat/9902067.
26. H. F. Fong, P. Bourges, Y. Sidis, L. P. Regnault, A. Ivanov, G. D. Gu, N. Koshizuka, and B. Keimer, Nature (in press); cond-mat/9902262.
27. S. M. Hayden, G. Aeppli, H. A. Mook, T. G. Perring, T. E. Mason, S.-W. Cheong, and Z. Fisk, Phys. Rev. Lett. 76, 1344 (1996).
28. S. Shamoto, M. Sato, J. M. Tranquada, B. J. Sternlieb, and G. Shirane, Phys. Rev. B 48, 13817 (1993).
29. P. Bourges, H. F. Fong, L. P. Regnault, J. Bossy, C. Vettier, D. L. Milius, I. A. Aksay, and B. Keimer, Phys. Rev. B 56, R11 439 (1997).
30. S. M. Hayden, G. Aeppli, P. Dai, H. A. Mook, T. G. Perring, S.-W. Cheong, Z. Fisk, F. Doggan, and T. E. Mason, Physica B 241–243, 765 (1998).
31. L. P. Regnault, P. Bourges, and P. Burlet, in Neutron Scattering in Layered Copper-Oxide Superconductors, edited by A. Furrer (Kluwer Academic, Dordrecht, 1998), pp. 85–134.
32. Y. Sasago, K. Uchinokura, A. Zheludev, and G. Shirane, Phys. Rev. B 55, 8357 (1997).