Metallic charge stripes in cuprates

J. M. Tranquada

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

Abstract

Some recent evidence for the existence of dynamic, metallic stripes in the 214-family of cuprates is reviewed. The mechanism of stripe pinning is considered, and changes in the charge density within stripes between the pinned and dynamic phases is discussed. From a purely experimental perspective, dynamic charge stripes are fully compatible with nodal “quasiparticles” and other electronic properties common to all superconducting cuprates.

Key words: stripes, neutron scattering, 214 cuprates

PACS: 74.72.Dn, 71.45.Lr, 75.30.Fv

1. Introduction

It is currently fashionable to consider phases that compete with superconductivity in the cuprates. These may be invoked to explain the pseudogap, or to characterize the state within a vortex core. Charge and spin stripes represent a specific type of order that has been experimentally observed to compete with superconductivity [1,2], to be pinned by vortices [3,4], and to be pinned by Zn impurities [5].

It has been speculated that dynamic stripes may underly the superconducting state, and, indeed, a plausible mechanism for superconductivity based on stripe correlations has been proposed [6,7]. In this paper, I review some of the evidence from cuprates in the 214 family that dynamic stripes exist and are metallic. The cause of stripe pinning and anomalies in the pinned state are also discussed.

2. Evidence for the stripe-liquid phase

While ordered charge stripes can coexist with superconductivity [1], stripe order is bad for superconductivity [2]. If stripes are to have a positive relevance to superconductivity in the cuprates, then they must be able to exist in a dynamic form. It has recently been shown that the insulating diagonal stripes of the layered nickelates can melt into a liquid phase [8]. The continuous evolution of the magnetic correlations from the ordered state to the disordered state provides direct evidence for dynamic charge stripes.

To obtain similar evidence for dynamic stripes in cuprates, inelastic neutron scattering experiments have been performed on La$_{1.875}$Ba$_{0.125}$CuO$_4$. Fujita et al. [9] have successfully grown a single crystal of this composition. The structure transforms from the low-temperature-orthorhombic (LTO) phase, common to La$_{2-x}$Sr$_x$CuO$_4$, to the low-temperature-tetragonal (LTT) phase on cooling through 60 K. Superlattice peaks characteristic of charge and spin stripe order appear below $\sim$ 50 K [9,10].

At 30 K, well within the stripe-ordered regime, the inelastic measurements reveal, in $\omega$-Q space, magnetic excitations rising steeply out of the superlattice positions (the measurements extend up to 12 meV) [10]. The scattering is fairly sharp in Q, and the intensity, corrected for the Bose factor, is independent of excitation energy, consistent with what one would expect for Q-integrated spin waves. On warming through the stripe melting transition and into the LTO phase, the magnetic excitations evolve continuously. At 65 K, the scattering peaks measured at a given energy have shifted to a slightly smaller splitting from the antiferromagnetic wave vector, they have broadened in Q width,
and there is a loss of low-energy weight in the Bose-factor-corrected intensity. (Similar results have been obtained on La$_{1.46}$Nd$_{0.4}$Sr$_{0.12}$CuO$_4$ by Ito et al. [11].)

The incommensurate magnetic excitations in the LTO phase are clearly connected with the magnetic order in the LTT phase. Given that the spin order is tied to charge-stripe order, it follows that the magnetic excitations in the disordered state provide direct evidence for dynamic charge stripes. The similarity of the spin correlations observed in La$_{1.875}$Ba$_{0.125}$CuO$_4$ with those found in La$_{2-x}$Sr$_x$CuO$_4$ [12,13] strongly indicates that dynamic stripes are a common feature of the 214 cuprates.

3. Stripe pinning mechanism

Kivelson, Fradkin, and Emery [14] have proposed that dynamic stripes may be thought of in terms of an electronic liquid-crystal model. Within this model, each charge stripe is modeled as a one-dimensional electron gas, and there is a competition between instabilities towards charge-density-wave (CDW) correlations and superconductivity within the stripes. Fluctuations of the stripes favor two-dimensional superconductivity, but pinning of straight, parallel stripes would lead to CDW order.

Hasselmann, Castro Neto, and Morriss Smith [15] have analyzed a model for the coupling between longitudinal charge dynamics with transverse fluctuations for a single stripe. They find that a zig-zag transverse lattice potential can induce a 4$k_F$ CDW state within the stripe. Such a transverse potential occurs within the CuO$_2$ planes of the LTT phase due to the modulations of the positions of the in-plane oxygens along the c axis. Thus, one might expect static stripe order in the LTT phase to be correlated with the appearance of a CDW gap in the optical conductivity. (4$k_F$ CDWs within charge stripes have also been considered by Zaanen and Oleś [16].)

Dumm et al. [17] have measured the in-plane optical conductivity in stripe ordered La$_{1.275}$Nd$_{0.6}$Sr$_{0.125}$CuO$_4$ vs. temperature. (Related results have been reported by Tajima et al. [18].) Down to 32 K the results look very similar to those for superconducting La$_{1.875}$Sr$_{0.125}$CuO$_4$, but at 5 K one observes a peak at finite frequency (~ 8 meV). Although Dumm et al. [17] have interpreted this feature in terms of localization effects, it also appears qualitatively consistent with CDW behavior.

4. Evidence that stripes are metallic

It has been argued above that stripe correlations are common among the 214 cuprates. One expects the existence of stripe correlations to have a strong impact on the electronic excitations [19]. Thus, it follows that characterizations of the electronic properties of La$_{2-x}$Sr$_x$CuO$_4$ should reflect the nature of dynamic stripes.

The in-plane optical conductivity observed for La$_{2-x}$Sr$_x$CuO$_4$ [17,18,20] looks quite similar, in both frequency and temperature dependence, to that measured on cuprates with higher superconducting transition temperatures [21]. Angle-resolved photoemission measurements on La$_{2-x}$Sr$_x$CuO$_4$ [22] reveal a distribution of spectral weight near the Fermi surface that is very similar to that measured on optimally-doped Bi$_2$Sr$_2$CaCu$_2$O$_{8+δ}$ [23]. In particular, spectral weight is found near the “nodal” point even in stripe-ordered La$_{1.4-x}$Nd$_{0.6}$Sr$_x$CuO$_4$ [22].

The existence of metallic properties in La$_{2-x}$Sr$_x$CuO$_4$ indicates that the dynamic charge stripes must be metallic. The fact that the electronic response of this material is essentially the same as that of other cuprates, together with the idea that stripes should influence the electronic properties, suggests that stripe correlations (or a related form of instantaneous charge inhomogeneity) could be ubiquitous in the superconducting cuprates. Further evidence for stripe correlations in a variety of cuprates is reviewed in [19].

5. Mid-gap states associated with stripes

Theoretical analyses of cuprates have predicted that the dopant-induced states associated with stripes (or more general forms of charge inhomogeneity) should appear within the charge-transfer gap of the parent insulator [24,25,26]. Such a concept should also apply to the diagonal charge stripes found in La$_{2-x}$Sr$_x$NiO$_{4+δ}$; indeed, the schematic density of states shown in Fig. 1 has been used recently to explain the mid-infrared peaks observed in optical conductivity [27]. The mid-gap states in the nickelates are empty at low temperature [28], so that these materials are insulating.

In contrast to the nickelates, one expects that ordered vertical stripes in the cuprates should be precisely $\frac{1}{4}$-filled with electrons, as indicated in Fig. 2. In this case, there is electron-hole symmetry, so that the off-diagonal conductivity should go to zero [29,30], as observed in the Hall-effect study of stripe-ordered La$_{1.4-x}$Nd$_{0.6}$Sr$_x$CuO$_4$ by Noda et al. [31]. The anomalous vanishing of the Hall coefficient occurs only when the stripes are ordered, as in the LTT phase; the Hall coefficient behaves “normally” in the LTO phase. To
reconcile this “normal” behavior with the existence of dynamic stripes, it is necessary to take account of the shift of the incommensurability with temperature measured by inelastic neutron scattering [10,11]. The incommensurability is proportional to the density of stripes. If the density of stripes changes while the net density of holes associated with stripes remains unchanged, then the electron (or hole) filling of the stripes will change. Any deviation from the precise $\frac{1}{4}$ filling of the ordered state will break particle-hole symmetry, and hence the anomalous Hall effect will disappear. The variation in stripe-filling in the dynamic phase is also consistent with frustration of the CDW instability by stripe fluctuations [14].

6. Conclusion

We have seen that there is strong evidence that dynamic stripes exist in La$_{2-x}$Sr$_x$CuO$_4$ and related cuprates. In such materials, photoemission studies show the existence of nodal “quasiparticles”, and the optical conductivity looks similar to that of many other superconducting cuprates. Pinning of stripes to lattice modulations appears to be associated with a CDW instability within the stripes. Changes in the electronic charge density within the charge stripes are correlated with the differences between pinned and dynamic stripes.

Experimentally, dynamic charge stripes are found to be compatible with the typical electronic properties of most cuprates. Of course, features such as nodal quasiparticles do not arise naturally out of theoretical models that focus on the one-dimensional nature of stripes. Thus, there remains a theoretical challenge to understand how the electronic properties of cuprates can be derived from dynamic stripes. It should be kept in mind that a lack of theoretical understanding does not invalidate the experimental case for metallic dynamic stripes.

7. Acknowledgements

I have benefited from numerous discussions with S. A. Kivelson and E. Fradkin, and I am especially grateful to my experimental collaborators M. Fujita, H. Goka, and K. Yamada. Research at Brookhaven is supported by the Department of Energy’s (DOE) Office of Science under Contract No. DE-AC02-98CH10886.

References

[1] J. M. Tranquada, J. D. Axe, N. Ichikawa, A. R. Moodenbaugh, Y. Nakamura, S. Uchida, Phys. Rev. Lett. 78 (1997) 338.

[2] N. Ichikawa, S. Uchida, J. M. Tranquada, T. Niemöller, P. M. Gehring, S.-H. Lee, J. R. Schneider, Phys. Rev. Lett. 85 (2000) 1738.

[3] B. Lake, H. M. Rønnow, N. B. Christensen, G. Aeppli, K. Lefmann, D. F. McMorrow, P. Vorderwisch, P. Smeibidl, N. Mangkorntong, T. Sasagawa, M. Nohara, H. Takagi, T. E. Mason, Nature 415 (2002) 299.
[4] B. Khaykovich, Y. S. Lee, R. W. Erwin, S.-H. Lee, S. Wakimoto, K. J. Thomas, M. A. Kastner, R. J. Birgeneau, Phys. Rev. B 66 (2002) 014528.

[5] K. Hirota, K. Yamada, I. Tanaka, H. Kojima, Physica B 241–243 (1998) 817.

[6] V. J. Emery, S. A. Kivelson, O. Zachar, Phys. Rev. B 56 (1997) 6120.

[7] E. W. Carlson, V. J. Emery, S. A. Kivelson, D. Orgad, Concepts in high temperature superconductivity, in: K. H. Bennemann, J. B. Ketterson (Eds.), The Physics of Conventional and Unconventional Superconductors, Springer-Verlag, 2003.

[8] S.-H. Lee, J. M. Tranquada, K. Yamada, D. J. Buttrey, Q. Li, S.-W. Cheong, Phys. Rev. Lett. 88 (2002) 126401.

[9] M. Fujita, H. Goka, K. Yamada, M. Matsuda, Phys. Rev. Lett. 88 (2002) 167008.

[10] M. Fujita, H. Goka, K. Yamada, J. M. Tranquada, (unpublished).

[11] M. Ito, Y. Yasui, S. Ikubo, M., Sato, M, Sato, A. Kobayashi, K. Kakurai, cond-mat/0301616.

[12] G. Aeppli, T. E. Mason, S. M. Hayden, H. A. Mook, J. Kulda, Science 278 (1997) 1432.

[13] K. Yamada, C. H. Lee, K. Kurahashi, J. Wada, S. Wakimoto, S. Ueki, Y. Kimura, Y. Endoh, S. Hosoya, G. Shirane, R. J. Birgeneau, M. Greven, M. A. Kastner, Y. J. Kim, Phys. Rev. B 57 (1998) 6165.

[14] S. A. Kivelson, E. Fradkin, V. J. Emery, Nature 393 (1998) 550.

[15] N. Hasselmann, A. H. Castro Neto, C. Morais Smith, Phys. Rev. B 65 (2002) 220511.

[16] J. Zaanen, A. M. Oleś, Ann. Phys. (Leipzig) 5 (1996) 224.

[17] M. Dumm, D. N. Basov, S. Komiya, Y. Abe, Y. Ando, Phys. Rev. Lett. 88 (2002) 147003.

[18] S. Tajima, N. L. Wang, N. Ichikawa, H. Eisaki, S. Uchida, H. Kitano, T. Hanaguri, A. Maeda, Europhys. Lett. 47 (1999) 715.

[19] S. A. Kivelson, I. P. Bindloss, E. Fradkin, V. Oganesyan, J. M. Tranquada, A. Kapitulnik, C. Howald, Rev. Mod. Phys. (accepted), cond-mat/0210683.

[20] F. Gao, D. B. Romero, D. B. Tanner, J. Talvacchio, M. G. Forrest, Phys. Rev. B 47 (1993) 1036.

[21] D. B. Romero, C. D. Porter, D. B. Tanner, L. Forro, D. Mandrus, L. Mihaly, G. L. Carr, G. P. Williams, Phys. Rev. Lett. 68 (1992) 1590.

[22] X. J. Zhou, T. Yoshida, S. A. Kellar, P. V. Bogdanov, E. D. Lu, A. Lanzara, M. Nakamura, T. Noda, T. Kakeshita, H. Eisaki, S. Uchida, A. Fujimori, Z. Hussain, Z.-X. Shen, Phys. Rev. Lett. 86 (2001) 5578.

[23] T. Valla, A. V. Fedorov, P. D. Johnson, Q. Li, G. D. Gu, N. Koshizuka, Phys. Rev. Lett. 85 (2000) 828.

[24] J. Zaanen, O. Gunnarsson, Phys. Rev. B 40 (1989) 7391.

[25] V. J. Emery, S. A. Kivelson, Physica C 209 (1993) 597.

[26] J. Lorenzana, G. Seibold, Phys. Rev. Lett. 89 (2002) 136401.

[27] C. C. Homes, J. M. Tranquada, Q. Li, A. R. Moodenaugh, D. J. Buttrey, Phys. Rev. B 67 (2003) 184516.

[28] J. Zaanen, P. B. Littlewood, Phys. Rev. B 50 (1994) 7222.