Physica C 481 (2012) 153–160

Contents lists available at SciVerse ScienceDirect

Physica C

journal homepage: www.elsevier.com/locate/physc

Detecting incipient stripe order in the high-temperature superconductor $Bi_2Sr_2CaCu_2O_{8+x}$

Eduardo H. da Silva Neto, Pegor Aynajian, Colin V. Parker, Ali Yazdani *

Joseph Henry Laboratories and Department of Physics, Princeton University, Princeton, NJ 08544, USA

ARTICLE INFO

Article history:
Available online 5 May 2012

Keywords:
Scanning tunneling spectroscopy
High temperature superconductors
Stripes
Correlated electrons
Pseudogap

ABSTRACT

We review recent spectroscopic mapping measurements on $Bi_2Sr_2CaCu_2O_{8+x}$ that establish experimental signatures of incipient stripe order. Model calculations show how to disentangle the effects of band structure and incipient order and allow us to model details of the energy-dependence of the observed modulations associated with incipient stripe order. Comprehensive doping and temperature studies reveal the correlation between the onset of the pseudogap and incipient stripe order in $Bi_2Sr_2CaCu_2O_{8+x}$, yet they also show that stripes are most likely the consequence of the pseudogap rather than its cause.

1. Introduction

Understanding the physical properties of high-temperature cuprate superconductors continues to be one of the most challenging problems in all of condensed matter physics. At the heart of the complexities of these materials is the fact that they show a remarkably wide range of electronic phenomena. The determination of their interplay and the identification of their individual roles in the mechanism of superconductivity are central to solving the cuprate puzzle. Since the pioneering work of Tranquada and co-workers [1], one particular phenomenon that has captured the attention of many in the field of high-T_c superconductivity is the formation of patterns of spin and charge, often referred to as stripes [2–5]. Such patterns have been anticipated in early calculations of properties of the CuO_2 plane, where balancing antiferromagnetic and Coulomb interactions result in the formation of periodic patterns of charges and spins [2–5]. Static stripe formation was first experimentally detected using neutron scattering in the La-based cuprates with a hole doping concentration of 1/8 (per copper atom), where structural distortion appears to pin stripes [6,7]. The appearance of static stripes also coincides with the suppression of the superconducting transition temperature, suggesting that there is a competition between stripes and superconductivity [8]. However, the exclusivity of static stripes to the La-based system has long raised the question of whether they are relevant to the fundamental physics of high-T_c superconductivity. Addressing this issue, Kivelson and co-workers have argued that in other cuprates, stripes may manifest themselves as a short-range or fluctuating order, and have provided specific ideas on how to detect such incipient ordering phenomena experimentally [9]. Therefore, observation of signatures of stripe order in various cuprates is important to determine whether stripes appear in compounds with no structural distortion. More importantly, such studies allow us to determine the connection between stripe formation and other phenomena in cuprates, in particular their relevance to the superconducting pairing mechanism and their relation to the appearance of the enigmatic pseudogap phase in underdoped samples [10].

In this paper, we review a series of measurements with the scanning tunneling microscope (STM) that provide strong evidence for the formation of incipient stripes in the high temperature superconductor $Bi_2Sr_2CaCu_2O_{8+x}$ across a wide range of temperature and doping [11]. These measurements show strong modulations in the local density of states that have the predicted signature of incipient stripe order. Moreover, we illustrate that these experimental results can be understood using model calculations of the scattering of quasiparticles from incipient stripe order, taking into account the electronic band structure of the $Bi_2Sr_2CaCu_2O_{8+x}$ [12]. Our calculations provide a framework within which we can understand the temperature dependence of the experimental results, following the signatures of incipient order both below and above the superconducting transition temperature. Examining the signature of incipient stripes as a function of temperature, we demonstrate that their appearance coincides with the onset of the pseudogap phase. Based on the studies of the doping dependence, we are able to show that it is unlikely that stripe formation causes the opening of the pseudogap; instead, the appearance of the pseudogap most likely results in the formation of the electronic correlations that allow short-range fluctuating stripes to nucleate over a wide range of the cuprate phase diagram.

* Corresponding author.
E-mail address: yazdani@princeton.edu (A. Yazdani).

0921-4534/$ - see front matter © 2012 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.physc.2012.04.017

STM studies have long been used to probe the local electronic structure of $Bi_2Sr_2CaCu_2O_{8+x}$, from those examining the influence of single impurities [13,14] and inhomogeneous pairing [15–17], to measurements of local density of states (LDOS) modulations due to the interference of d-wave quasiparticles caused by their scattering from impurities in the superconducting state [18]. Early evidence of local ordering from STM measurements came from experiments above the superconducting transition temperature [19] and near vortices in the superconducting state [20]. Over the last decade, however, the difficulty in disentangling the electronic modulations associated with incipient order from those due to quasiparticle interference has obfuscated the interpretation of spatial modulations of the density of states in STM measurements [9,21,22]. Furthermore, any evidence of ordering would also have to be reconciled with the fact that probes sensitive to long-range order and reorganization of electronic states have indicated the absence of long-range static stripes in $Bi_2Sr_2CaCu_2O_{8+x}$ samples at any doping [23].

2. Signatures of incipient stripe order

Fig. 1 shows examples of real space low-energy conductance mapping $G(\mathbf{r},V) = dI/dV(\mathbf{r},V)$ with the STM on an underdoped $Bi_2Sr_2(Ca,Dy)Cu_2O_{8+x}$ sample (UD35) carried out at three different temperatures corresponding to the superconducting state at $T < T_c$, the fluctuating paired state with weak diamagnetic response [24,25] $T_c < T < T_o$, and the pseudogap state at $T_o < T < T^*$. Discrete Fourier transforms (DFTs) of the conductance maps display strong peaks at wavevectors marked Q^* (Fig. 1d–f) along the Cu–O bond direction in all three temperature ranges. These peaks correspond to the checkerboard-like patterns seen in $G(\mathbf{r},V)$ (Fig. 1a–c), with a real space periodicity of approximately 4a, where a corresponds to the distance between nearest neighbor Cu atoms. Similar strong features appear at a larger wavevector, marked Q^{**}, also along the Cu–O bond direction.

At temperatures below T_c, the DFTs of the conductance maps show additional peaks that have been previously associated with the interference of Bogoliubov-de Gennes quasiparticles (BdG-QPIs) in the superconducting state [18,22,26,27]. Their contribution to the spatial variation of the density of states with superconducting origin can be further enhanced by the use of a ratio of conductance maps [26] $Z(\mathbf{r},V) = G(\mathbf{r},+V)/G(\mathbf{r},-V)$, as demonstrated in Fig. 1g–i (peaks marked q_2–q_7). All the modulations in the LDOS, including those corresponding to Q^*, appear to have energy-dependent wavelengths near the Fermi energy (±50 mV) throughout the entire temperature range, a behavior not expected for static long-range order (see Fig. 3 below). However, a distinction between Q^* and Q^{**}, and the other wavevectors that occur due to impurity-induced interference becomes evident when analyzing their phase properties across a range of energies.

We expect that incipient ordering phenomena (e.g., charge density wave) manifest themselves as modulations in STM conductance maps with similar phases across a range of energies, whereas modulations of LDOS due to impurity-induced quasiparticle interference are phase incoherent [9]. To distinguish which features are associated with incipient order, we construct the quantity

$$S(k_x, k_y, V_0) = \left|\int_{-V_0}^{V_0} G(k_x, k_y, V)\right| \Big/ \int_{-V_0}^{V_0} |G(k_x, k_y, V)| dV \quad (1)$$

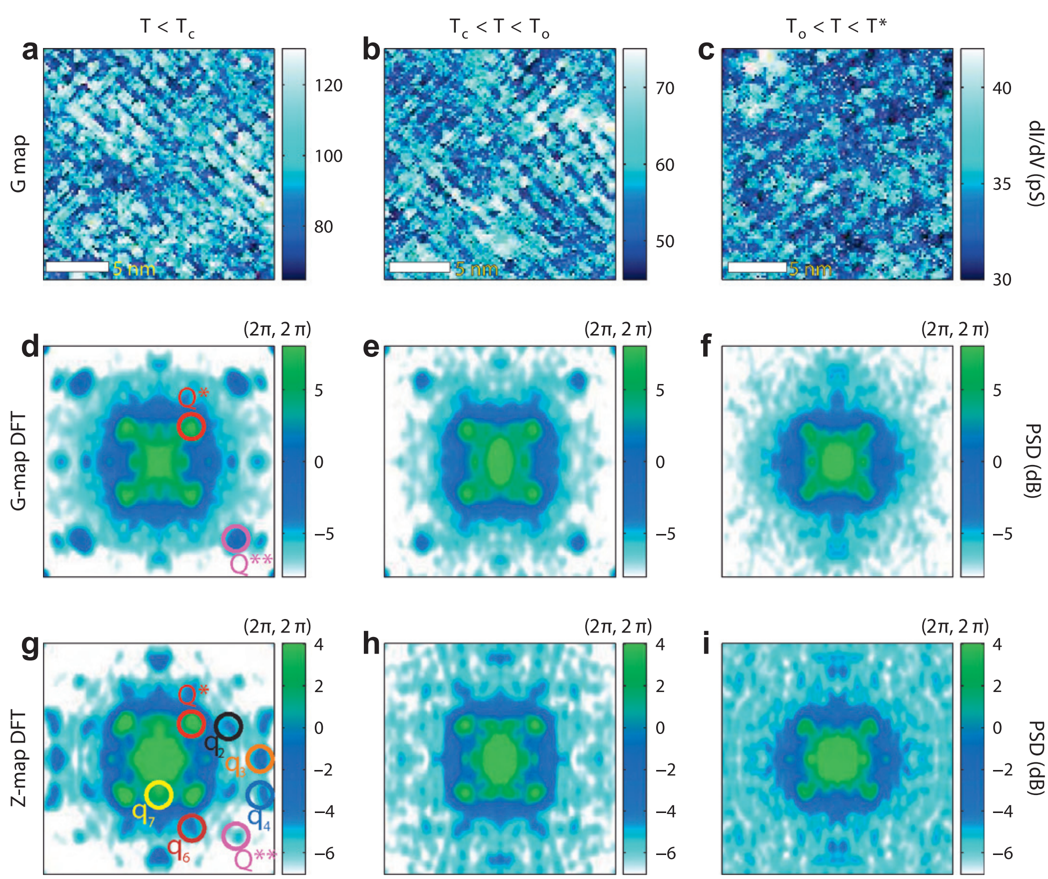

Fig. 1. Real space low-energy conductance maps $G(\mathbf{r},V)$ at $V = 10$ mV on UD35 ($T_c = 35$ K) carried out at 8 K (a), 41 K (b), and 122 K (c). At all temperatures, strong electronic bond-oriented modulations are observed. The white scale bars in (a–c) correspond to 5 nm. The corresponding DFTs of $G(\mathbf{r},V = 10\text{ mV})$ and of the $Z(\mathbf{r},V = 10\text{ mV})$ are respectively shown in (d–f) and (g–i), which display strong peaks at several wavevectors as marked in (g). Only the peaks marked as Q^* and Q^{**}, corresponding to the real space modulations in (a–c), survive to temperatures well above T_c. Figure reproduced from [11].