Tendencies toward nematic order in YBa$_2$Cu$_3$O$_{6+\delta}$: Uniform distortion vs. incipient charge stripes

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Abstract. Recent neutron scattering and transport data obtained on underdoped YBa$_2$Cu$_3$O$_{6+\delta}$, with strong signatures of rotation symmetry breaking at low temperatures, point toward electron-nematic order in the charge sector. Such order may originate from a uniform distortion with $d$-wave symmetry or as a precursor of a uni-directional stripe phase. Here, we discuss whether the neutron scattering data can be linked to incipient charge stripes. We employ and extend a phenomenological model for collective spin and charge fluctuations and analyze the resulting spin excitation spectrum under the influence of lattice anisotropies. Our results show that the experimentally observed temperature-dependent magnetic incommensurability is compatible with a scenario of incipient stripes, the temperature dependence being due to the temperature variation of both strength and correlation length of the charge stripes. Finally, we propose further experiments to distinguish the possible theoretical scenarios.

1 Introduction

The interplay of different ordering tendencies is a recurring theme in unconventional superconductors – this applies to cuprates, iron pnictides, and heavy-fermion superconductors. In high-$T_c$ superconducting cuprates, phenomena of spontaneous lattice symmetry breaking have been observed inside the pseudogap regime [1,2]. In particular, stripe order in both the spin and charge sectors has been established in the La$_{2-x}$Sr$_x$CuO$_4$ (or 214) family [3], while in YBa$_2$Cu$_3$O$_{6+\delta}$ (YBCO), signatures of electronic nematic order have been reported [4,5]. Given the similarities in the spin excitation spectra at intermediate energies – the so-called hourglass spectrum – across different cuprate families, it has long been proposed that stripes might be a common origin of incommensurate low-energy spin fluctuations [1,2,6]. This view has been fueled by the observation of stripe-like modulations in the charge sector on the surface of Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ and Ca$_2$Na$_2$CuO$_2$Cl$_2$ using scanning tunneling microscopy (STM) [7–9]. It has been argued that a picture of spatially disordered (i.e., slowly fluctuating or disorder-pinned) stripes is broadly consistent with both neutron and STM data [10,11]. In this scenario, modulations in the charge sector are driving the incommensurabilities in the spin sector. This view is compatible with the phase diagrams of various 214 cuprates, where charge order is established at a higher temperature than spin order, i.e., charge stripes can exist without ordered magnetism over a range of temperatures.

Recent experimental data on de-twinned YBCO, where both neutron scattering [4] and thermoelectric transport [5] data show distinct in-plane anisotropies below a doping-dependent onset temperature, have suggested to consider electron-nematic order, i.e., rotation symmetry breaking with translation symmetry preserved, as a separate player. In fact, simple model calculations for the anisotropy of the spin excitations [12] and that of the Nernst signal [13]
based on uniform distortions describing nematic order were found to describe salient aspects of the data. This naturally prompts the question whether nematic or stripe order should be considered as the “primary” order parameter. This issue is of importance, as it pertains to proposals which link the origin of the pseudogap in underdoped cuprates to a symmetry-breaking order competing with superconductivity.

In this paper, we shall attempt to answer the question whether the neutron data of Ref. [4] are consistent with a scenario of spatially disordered charge stripes as advocated in Ref. [10]. To this end, we study the coupled order-parameter field theory of Ref. [10] in a regime of a small spin gap under the influence of lattice anisotropies. Using plausible assumptions for the temperature dependence of the collective charge degrees of freedom, we determine the anisotropy of the low-energy spin fluctuations and compare them to the data of Ref. [4]. Doing so, we find the answer to the above question to be a tentative “yes”; hence, we provide here a mechanism for the observed temperature-dependent incommensurability [4] alternative to the one of Ref. [12]. Finally, we propose further experiments to discriminate between available theoretical scenarios.

The body of the paper is organized as follows: To set the stage, we shall begin with general remarks about order parameters, symmetries, and phase diagrams in Sec. 2. We then turn to the spin dynamics and describe in Sec. 3 the coupled order-parameter theory of Ref. [10], with appropriate modifications. Sec. 4 presents the numerical results for the dynamic spin susceptibility, together with the analysis of the low-energy incommensurability. A discussion of experimentally relevant issues and an outlook will close the paper.

2 Stripe and nematic order

In the context of uni-directional stripe order in quasi-2d systems, order parameters for spin and charge density waves as well as for rotational symmetry breaking can be considered. In the following we shall discuss a continuum description which is appropriate for slowly varying order-parameter fields. For reasons explained below, the calculation in Sec. 3 will instead use a lattice formulation.

The charge density wave (CDW) requires a pair of complex scalar fields $\phi_{cx}, \phi_{cy}$ for the two CDW directions with wavevector $Q_{cx}$ and $Q_{cy}$. Then, the charge density follows

$$\langle \rho(R, \tau) \rangle = \rho_{av} + \text{Re} \left[ e^{iQ_{cx} \cdot R} \phi_{cx}(R, \tau) \right].$$

Similarly, there is a pair of complex vector fields $\phi_{sax}$, $\phi_{say}$ describing spin density waves (SDW) with wavevectors $Q_{sx}$ and $Q_{sy}$. For cuprates at dopings above 5%, order has been found at $Q_{sx} = 2\pi(0.5 \pm 1/M, 0.5)$, $Q_{sy} = 2\pi(0.5 \pm 1/M)$ and $Q_{cx} = (2\pi/N, 0)$, $Q_{cy} = (0, 2\pi/N)$, where $M$ and $N$ are the real-space periodicities which follow $M = 2N$ to a good accuracy [1-3]. Finally, there is an Ising scalar $\phi_n$ for $l = 2$ spin-symmetric electron-nematic order at wavevector $Q = 0$. The dynamics of any of these order parameters should be described by an appropriate $\phi^4$ (or Landau-Ginzburg-Wilson) action. Other ordering phenomena, e.g., uniform and modulated superconducting pairing, shall not be of interest here.

Biquadratic local couplings between all order parameters are generically symmetry allowed. For instance, a term $v[|\phi_{cx}(r, \tau)|^2|\phi_{cy}(r, \tau)|^2$, which couples horizontal and vertical charge stripes, decides about repulsion or attraction between $\phi_{cx,y}$, i.e., $v > 0$ will lead to uni-directional (stripe) order where $v < 0$ results in bi-directional (checkerboard) order.

More interesting are couplings involving one order parameter linearly. Those terms are strongly constrained by symmetry and momentum conservation. A nematic order parameter $\phi_n$ in a tetragonal environment couples to CDW and SDW according to

$$\kappa_1|\phi_{cx}|^2 - |\phi_{cy}|^2 + \kappa_2|\phi_{sax}|^2 - |\phi_{say}|^2,$$

Note that the YBCO crystal structure is orthorhombic due to the presence of CuO chains, such that the in-plane rotation symmetry is broken from the outset. Hence, there is no symmetry-breaking electronic phase transition, but the common assumption is that the structural anisotropies are enhanced by correlation effects at low temperatures, signaling the tendency toward electron-nematic order.

$^2$ This continuum description cannot capture modulations with wavevectors significantly different from $Q_{cx}$ and $Q_{cy}$. 