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# Electronic liquid crystal physics of underdoped cuprates

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ABSTRACT

Recent observations of broken symmetries have partly demystified the pseudogap phase. Here we review evidence for long-range intra–unit-cell (IUC) nematic order and its unexpectedly strong coupling to the phase of the fluctuating stripes in the pseudogap states of underdoped $Bi_2Sr_2CaCu_2O_{8+\delta}$. In particular, we focus on the analysis techniques that reveal this evidence in scanning tunneling spectroscopy data, the definition of the extracted IUC nematic order parameter, and a phenomenological theory of the coupling between the IUC nematic order and the previously reported coexisting fluctuating stripes. We also present a microscopic mechanism of IUC nematic order driven by on-site and near-neighbor repulsions. Finally we discuss open questions in the context of these results.



## 1. Introduction

The wide variety of systems discussed in this special issue form strong empirical evidence that electronic liquid crystals generically emerge out of correlated electronic systems in a quantum regime. On the one hand, the uncertainty principle challenges against a single sweep numerical solution of a fermionic hamiltonian, when neither the single particle kinetic energy nor the inter-particle interaction energy can be ignored. On the other hand, the conflict between kinetic energy and interaction energy indeed appear to find a compromise in electronic liquid crystals [1], as first proposed in Ref. [2]. This observation invites what we call "middle-up/down approach" to quantum phenomena of correlated systems: seeking insights in experimental data from the perspective of symmetries (middle → down) and then feeding those insights into theory (middle → up). What guides this approach are symmetry principles.

From symmetry principles, electronic nematic and smectic phases are analogues of liquid crystalline nematic and smectic phases. When a collection of anisotropic molecules called "nematogens" are in a liquid phase, the system is invariant under infinitesimal translations and rotations. In a nematic phase, the system still has this translational symmetry but the rotational symmetry is broken and the system is only symmetric under a rotations by 180°. In a smectic phase, the translational symmetry is also reduced in one of spatial directions and a modulated density forms in that direction. This modulation automatically breaks rotational symmetry in space as well. Electronic nematic and smectic phases share similar symmetries. The smectic phase would be a kind of unidirectional charge density wave while a nematic phase could be viewed in two ways, as the melting of the unidirectional waves or as a shape instability of the Fermi surface (see Fig. 1). However, the order parameters of these phases is different from their classical counter parts because the highest symmetry they may have is not that of an isotropic space but that of, for example, a square lattice [1].

However, electronic liquid crystals as electronic phases in the quantum regime face new challenges and possibilities. One new challenge is in figuring out a mechanism for nematic formation without a pre-formed "nematogen". In liquid crystal nematics the prolonged shape of the "nematogen" molecule provides an entropy driven mechanism: at low temperatures it is easier for them to move around if they all point in the same direction. For electronic nematics, a mechanism for spatial symmetry breaking is more subtle though an extended range interaction is one possibility. One new phenomena arising in the electronic version of liquid crystals are the quantum phase transitions that exist between them. While phase transitions between different liquid crystalline phases are determined as a balance between energy and entropy at finite temperature, transitions between different electronic liquid crystal phases can be controlled even at zero temperature by quantum fluctuations and can lead to novel non-Fermi liquid physics.

In this article, we review our recent progress in understanding electronic liquid crystal physics using a "middle-up/down approach" to underdoped cuprates. Cuprates are paradigmatic strongly correlated systems whose electronic properties change dramatically as one scans through the phase diagram in Fig. 2. In the underdoped region below a doping- and probe-dependent temperature scale $T^*$, cuprates exhibit a loss of low energy states

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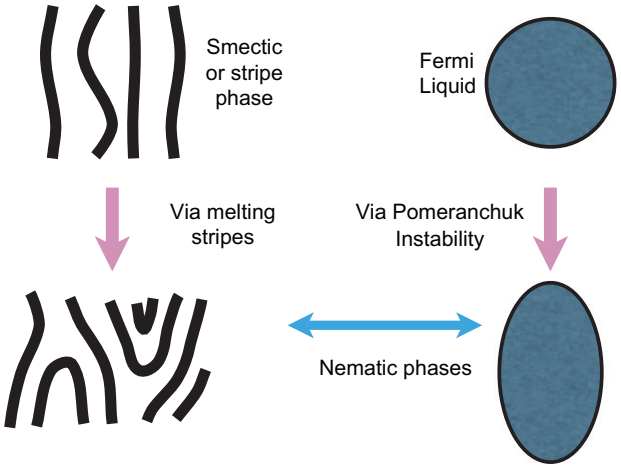


**Fig. 1.** Two perspectives on electronic liquid crystals. Orientational order can arise as a shape instability of the Fermi surface (right). Conversely, it could arise from the melting of a unidirectional wave (stripe) pattern through the proliferation of dislocations. The resulting phases in each case can be adiabatically connected to each other.

below some energy scale: a "pseudogap". Whether this region involves a spontaneous symmetry breaking has been a topic of fierce debate ever since the discovery of cuprates. At the simplest level, this debate has been waiting for evidence of symmetry breaking. Remarkably, such evidence has started to accumulate recently [3–7] and here we will focus on evidence of symmetry breaking towards the formation of an electronic liquid crystal in $Bi_2Sr_2CaCu_2O_{8+\delta}$.

The rest of the article is organized as follows. In Section 2, we will discuss an intra–unit-cell (IUC) nematic order parameter and a smectic order parameter as defined and measured in Ref. [7]. In Section 3, a proposal for an effective theory describing the coupling between the two order parameters and its validity as tested in Ref. [8] are reviewed. In Section 4, a microscopic mechanism for IUC nematic and other IUC symmetry breaking, based on inter-site repulsion in the Emery model for $CuO_2$ plane [9] is discussed. We close the article in Section 5 with a discussion of recent theoretical developments on the subject and interesting future directions.

## 2. Intra–unit-cell electronic nematic and fluctuating smectic

In general, the challenge in establishing a broken symmetry is in devising an order parameter that can be pursued by experimental probes. Even when the target order parameter is known, a new type of broken symmetry may require a new experimental technique. On the other hand, a new technique may call for a new order parameter that can take advantage of it. The accumulation of scanning tunneling spectroscopy (STS) data of heterogeneous patterns (see Fig. 3a and b), called for a new order parameter to turn the heterogeneous images into theoretical inputs.

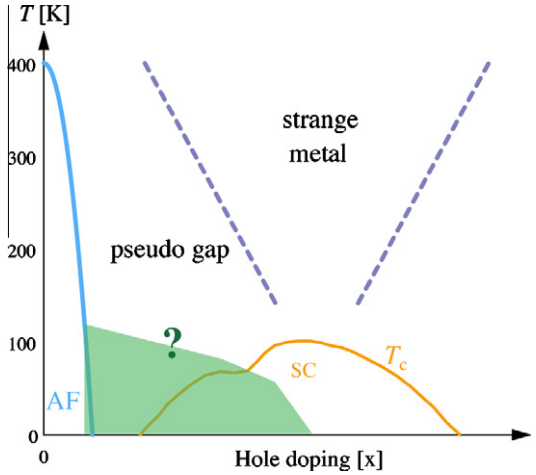


**Fig. 2.** A schematic phase diagram for cuprates.

Since the concept of spontaneous symmetry breaking was established, bulk measurements have been perfected. At the same time we have developed theoretical formalisms best suited to aid the connection between bulk measurements and the physics of symmetry breaking and phase transitions. However, apparently a heterogeneity at the nano-scale is common among strongly correlated systems. Moreover, such heterogeneity is likely due to cooperation between quenched disorder and interaction effects such as a tendency to form a ELC state. The existence of heterogeneity and the possibility of its intrinsic origin propelled developments in local scanning probes. However the lack of suitable theoretical formalism prevented the atomic scale STS data (see for instance Fig. 3), from providing an intermediate length scale information of ordered regions.

We had two goals in developing local measures of electronic liquid crystal ordering: (i) to distinguish nematic from smectic and (ii) to *coarse-grain* atomic scale information and define order parameter fields. We achieved both goals in Ref. [7] by going to Fourier space. In position space, patterns with a particular modulation period breaking translational symmetry of lattice and those that respect lattice translational symmetry are all superposed (see Fig. 3). However, in Fourier space these two signals are separated as shown in the inset of Fig. 4a. All information that respect lattice translation are carried by the Bragg peaks and modulation signals that break lattice translation symmetry are carried by broad peaks near $\pm\vec{S}_x \approx (\pm 3/4, 0)2\pi/a$ and $\pm\vec{S}_y \approx (0, \pm 3/4)2\pi/a$. By focusing on spatial variations in the STS data at each of the two atomic scale wavelengths, an IUC nematic order parameter fields and smectic order parameter fields can be defined.

An IUC nematic order parameter associated with a real space data $M(\vec{r})$ is

$$O_N[M] = \frac{1}{2}[\tilde{M}(\vec{Q}_y) - \tilde{M}(\vec{Q}_x) + \tilde{M}(-\vec{Q}_y) - \tilde{M}(-\vec{Q}_x)], \quad (1)$$

where $\tilde{M}(\vec{q})$ is complex valued two-dimensional Fourier transform of $M(\vec{r})$:

$$\tilde{M}(\vec{q}) = \frac{1}{\sqrt{N}} \sum_{\vec{R}+\vec{d}} M(\vec{R}, \vec{d}) e^{-i\vec{q}_x \cdot \vec{d}} \quad (2)$$

and $\vec{Q}_x = (2\pi/a_0, 0)$ and $\vec{Q}_y = (0, 2\pi/a_0)$ are two inequivalent Bragg peaks associated with unit cell dimension $a_0$. In Eq. (2) $\vec{R}$ is a Bravis lattice vector and $\vec{d}$ is a basis vector pointing to atomic positions within the unit cell. As defined, $O_N$ is only sensitive to signals that respects lattice periodicity and it detects an inequivalence between the *x*- and *y*-directions. Hence $O_N$ has all the features one expects of electronic nematic order parameter, which is supposed to be a headless vector [1]. Furthermore, that $O_N$ is a real number is consistent with the expectation that reduction of $C_{4v}$ down to $C_{2v}$ should be through an Ising-like order parameter [13]. However, the proposed IUC nematic order parameter Eq. (1) comes with two requirements on $M(\vec{r})$: (i) accurate registry of atomic sites for the phase of Fourier transform, and (ii) subatomic resolution. The latter condition is tied to the fact that $O_N \neq 0$ measures intra–unit-cell variations in $M(\vec{r})$.

To gain insight into $O_N$ as a measure of "intra–unit-cell" ordering, consider a simple distribution of $M(\vec{r})$ such that $M(\vec{r})$ is nonzero only at *Cu* sites and $O_x$, $O_y$ sites on a $CuO_2$ plane. Then