Intra unitcell nematic in the pseudogap states?

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M.J. Lawler et al, 2009
Lessons from Ruthenates
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Nematic is strong correlation physics
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Nematic is strong correlation physics

Nematic is sensitive to local disorder
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Symmetry breaking field?
Lessons from Ruthenates

Nematic is strong correlation physics

Nematic is sensitive to local disorder

Symmetry breaking field?

Scanning local probes?
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Cornell

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Cornell

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St. Andrews, UBC

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Cornell
Piet Mondrian, 1915. Says he is searching for hidden order in nature...

Ocean 5, Guggenheim collection, Venice
2nm

0.71

1.48

Dy-Bi2212 UD45K
Lawler et al. 2009, identified hidden order in the pseudogap state of underdoped Bi$_2$212.
Intra unitcell nematic in the pseudogap states?

- Where we started
- BSCCO: got nematic?
  - Definition
  - Analysis
- Meaning?
Local measure of broken symmetry?

**dI/dV(ω)-map**

OD T_c=86K

**R-map**

UD T_c=45K (p=0.08)

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**Figure S7 a-f.** A series of images displaying the real space conductance ratio Z as a function of energy rescaled to the local pseudogap value, \( e = E/\Delta_q(r) \). Each pixel location was rescaled independently of the others. The common color scale illustrates that the bond centered pattern appears strongest in \( Z \) exactly at \( E = \Delta_q(r) \).

**Z-map(ω)**

UD T_c=45K
Local measure of broken symmetry?

UD $T_c=45K$ ($p=0.08$)  
Local measure of broken symmetry?

HAMLET: Do you see yonder cloud that's almost in shape of a camel?
POLONIUS: By th'mass, and 'tis like a camel indeed.
HAMLET: Methinks it is like a weasel.
POLONIUS: It is backed like a weasel.

--W. Shakespeare

UD $T_c=45K$ (p=0.08)  Kohsaka et al, Nature 454, 1072 (2008)
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Challenge: An objective measure
BSCCO, got nematic?

Defining the local order parameters
Candidate broken symmetries

• Translational symmetry
  \[ \hat{T}_a, \hat{T}_b \]

• Rotational symmetry
  \[ \hat{R}_{\pi/2} \]

Can we separately measure?

Need a \[ \hat{T}_a, \hat{T}_b \] preserving order parameter
Local measure of broken symmetry?

Position space

2nm

$Z(r, e=1)$
Local measure of broken symmetry?

Position space

\[ Z(r, e=1) \]

2nm

Fourier space
Local measure of broken symmetry?

Position space $Z(r, e=1)$

Fourier space $Q_x$ vs $Q_y$?
Local measure of broken symmetry?

Position space

\[ Z(r,e=1) \]

\[ Q_x \text{ vs } Q_y ? \]

\[ Q^*_x \text{ vs } Q^*_y ? \]

Fourier space
• Bragg peak

\[ \tilde{Z}(\vec{Q}_x) = \frac{1}{\sqrt{N}} \sum_{\vec{R} + \vec{d}} Z(\vec{R} + \vec{d}) e^{-i\vec{Q}_x \cdot \vec{d}} \]

\[ \vec{Q}_x = (2\pi/a, 0) \]

• Nematic OP

\[ \mathcal{O}_N \equiv \tilde{Z}(\vec{Q}_x) - \tilde{Z}(\vec{Q}_y) + \tilde{Z}(-\vec{Q}_x) - \tilde{Z}(-\vec{Q}_y) \]

Preserves lattice translation

M.J. Lawler et al, 2009
• Bragg peak

\[ \tilde{Z}(\tilde{Q}_x) = \frac{1}{\sqrt{N}} \sum_{\tilde{R}+\tilde{d}} Z(\tilde{R} + \tilde{d}) e^{-i\tilde{Q}_x \cdot \tilde{d}} \]

\[ \tilde{Q}_x = (2\pi/a, 0) \]

• Nematic OP

\[ \mathcal{O}_N \equiv \tilde{Z}(\tilde{Q}_x) - \tilde{Z}(\tilde{Q}_y) + \tilde{Z}(-\tilde{Q}_x) - \tilde{Z}(-\tilde{Q}_y) \]

⇒ Measures $C_4$ breaking

⇒ Preserves lattice translation

M.J. Lawler et al, 2009
Nematic OP $\mathcal{O}_N$ and microscopics

\[
\tilde{Z}(\vec{Q}_x) = \tilde{Z}_{\text{Cu}} - \tilde{Z}_{O_x} + \tilde{Z}_{O_y}, \quad \tilde{Z}(\vec{Q}_y) = \tilde{Z}_{\text{Cu}} + \tilde{Z}_{O_x} - \tilde{Z}_{O_y}
\]

$\mathcal{O}_N \propto (\tilde{Z}_{O_x} - \tilde{Z}_{O_y})$

M.J. Lawler et al, 2009

\[\text{Need O sites}\]

CuO$_2$ plane

Intra unitcell Nematic: $C_4 \rightarrow C_2$
Local version of Nematic OP $\mathcal{O}_N(r)$

- What real space information leads to a given momentum space peak?

$$\hat{Z} (\vec{Q}, \bar{x}) = \text{low pass}_{\Lambda} \left[ Z(\bar{x}, e) e^{i\vec{Q} \cdot \bar{x}} \right]$$

$$= \sum_{\bar{x}'} Z(\bar{x}', e) e^{i\vec{Q} \cdot \bar{x}'} f_{\Lambda} (\bar{x}' - \bar{x})$$

- Local order parameter:

$$\mathcal{O}_N(\bar{x}) = \hat{Z} (\vec{Q}_x, \bar{x}) - \hat{Z} (\vec{Q}_y, \bar{y}) + \hat{Z} (-\vec{Q}_x, \bar{x}) - \hat{Z} (-\vec{Q}_y, \bar{y})$$

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BSCCO, got nematic?

Piezo Drift
Key: Atomic registry with the lattice
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Key: Atomic registry with the lattice
Correct Piezo drift

Undistorts and fixes phase of Bragg peaks
Correct Piezo drift

Undistorts and fixes phase of Bragg peaks
BSCCO, got nematic?

Listening to the Bragg peaks
Nematic ordering in UD 45

\[ \mathcal{O}_N \equiv \tilde{Z}(\vec{Q}_x) - \tilde{Z}(\vec{Q}_y) + \tilde{Z}(-\vec{Q}_x) - \tilde{Z}(-\vec{Q}_y) \]

Extracted from published data, \( T=4K \)

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Extracted from published data, \( T=4K \)

Dy-Bi2212 UD45K

Linecut : FT-Z(r,e=1)

FT-Z(r,e=1)

FT-Topo

Intensity (arb. unit)

q (2π/a₀)
Nematic domains

• Shift $Q_x$, $Q_y$ to origin (“tune to the channel”)

$O_N(r,e)$

• Low pass filter (long distance physics)

2nm
Nematic domains

- Shift $Q_x$, $Q_y$ to origin ("tune to the channel")
- Low pass filter (long distance physics)

$O_N(r,e)$

- Purple
- Gold

2nm
Nematic domains

\[ O_N(r,e=1) + Z(r,e=1) \]

Dy-Bi2212 UD45K

M.J. Lawler et al, 2009
BSCCO, got nematic?

Listening to the $Q^*$ peaks
Smectic ordering in UD 45

\[ \mathcal{O}_S \equiv \tilde{Z}(\tilde{Q}_x^*) - \tilde{Z}(\tilde{Q}_y^*) + \tilde{Z}(-\tilde{Q}_x^*) - \tilde{Z}(-\tilde{Q}_y^*) \]

\[ \mathcal{O}_S \quad \text{average suppressed throughout} \]

Smectic domains

- Shift $Q^*_x$, $Q^*_y$ to origin ("tune to the channel")
- Low pass filter (long distance physics)

Severely fluctuating in space through out

Smectic domains

- Shift $Q^*_x$, $Q^*_y$ to origin ("tune to the channel")
- Low pass filter (long distance physics)

Severely fluctuating in space throughout

Meanings?
Hypothesis: longer ranged orientational ordering?
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Example:

Weak Pinning and Hexatic Order in a Doped Two-Dimensional Charge-Density-Wave System

Hongjie Dai, Huifen Chen, and Charles M. Lieber

*Departments of Chemistry and Applied Physics, Columbia University, New York, New York 10027*

(Received 11 July 1990; revised manuscript received 25 February 1991)

Scanning-tunneling microscopy has been used to characterize the effects of Nb impurities on the incommensurate charge-density-wave (CDW) phase in $1T$-TaS$_2$. Real- and reciprocal-space data indicate that disorder in the CDW is due to dislocations and small random rotations of the CDW. The dislocations destroy translational order; however, calculations show that the orientational order is long range.
Hypothesis: longer ranged orientational ordering?

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Microscopic Model

CuO$_2$ plane

Extended Hubbard Model

V. Emery, PRL 58, 2974 (1987)
C. Varma et al, PRL 58, 2974 (1987)
Microscopic Model

CuO

CuO₂ plane
Microscopic Model

One-band Model
Hubbard or t-J

Cu
Microscopic Model

One-band Model
Hubbard or t-J

Intra unitcell Nematic in Pseudogap phase
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Microscopic Model

Intra unitcell Nematic in Pseudogap phase

M.J. Lawler et al, 2009

One-band Model
Hubbard or t-J

Extended
Hubbard Model

Other competing orders?

- Congruent with

Intra unitcell Nematic in Pseudogap phase

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Other competing orders?

- Congruent with Charge nematic

Intra unitcell Nematic in Pseudogap phase

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Other competing orders?

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Intra unitcell Nematic in Pseudogap phase

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Other competing orders?

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Intra unitcell Nematic in Pseudogap phase

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translation preserving magnetism
Other competing orders?

- Congruent with Charge nematic
- Intra unitcell Nematic in Pseudogap phase
  
  M.J. Lawler et al, 2009

- Relation unclear yet
- Translation preserving magnetism
Other competing orders?

- Congruent with
  Charge nematic
- Translation preserving magnetism
- Relation unclear yet
  : various $\hat{T}_a, \hat{T}_b$ breaking orders

Intra unit cell Nematic in Pseudogap phase
M.J. Lawler et al, 2009
Other competing orders?

• Congruent with

Intra unitcell Nematic in Pseudogap phase

M.J. Lawler et al, 2009

Charge nematic

translation preserving magnetism

• Relation unclear yet

: various $\hat{T}_a, \hat{T}_b$ breaking orders

Flux phase,
DDW,
valence bond solid,
spin/charge
smectic
Other systems?

Intra unitcell Nematic in Pseudogap phase

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Other systems?

Intra unitcell Nematic in Pseudogap phase

M.J. Lawler et al, 2009
Other systems?

Intra unitcell Nematic in Pseudogap phase

M.J. Lawler et al, 2009

Ruthenates

YBCO

(R. Daou et al)
Other systems?

Intra unitcell Nematic in Pseudogap phase

M.J. Lawler et al, 2009

Ruthenates

YBCO

(R. Daou et al)

Hinkov et al + K. Sun et al
Other probes?
Other probes?

Fourier space
Other probes?

Fourier space

$Q_x \text{ vs } Q_y$?

$Q^*_x \text{ vs } Q^*_y$?
Other probes?

Fourier space

- Diffuse scattering in bulk probe

$Q_x$ vs $Q_y$?

$Q^*_x$ vs $Q^*_y$?
Other probes?

Fourier space

- Diffuse scattering in bulk probe
- Other local probes? Go after oxygens?

$Q_x$ vs $Q_y$?

$Q_x^*$ vs $Q_y^*$?
Intra unitcell nematic in the pseudogap states?
Intra unitcell nematic in the pseudogap states?

Prepared identification
• Nematic d-wave QPC, license to exist

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Theory

Experiment

- Local broken C4 symmetry
- Importance of Oxygens

UD $T_c$=45K ($p=0.08$)
Theory

- Nematic d-wave QPC, license to exist
  

Experiment

- Local broken C4 symmetry
- Importance of Oxygens

UD Tc=45K (p=0.08)

Domain average  ➔  Arc