Lect2. New probes and new reality

Eun-Ah Kim
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probing possible QPT in the presence of disorder

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probing possible QPT in the presence of disorder with scanning probes

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$O_N(x)$ map at $E = 6.0 \text{meV}$
$O_N(x)$ map at $E = 6.0\text{meV}$

$O_N(x)$ map at $E = 102.0\text{meV}$
New probes and new reality

• Effect of disorder on QPT’s

• Cuprates, a case study: got nematic?

• Look out
Effects of disorder on QPT’s

• Disorder is quenched
  - perfectly correlated along the $\tau$ direction
  - correlations increase the disorder effect (harder to average out fluctuation)

Disorder generically has stronger effects on QPT’s than on classical transitions

Effects of disorder on Phase Transitions

- Defects, impurities are always present
- Random field v.s $T_c$: different effects on the classical Ising PT. (Imry-Ma, v.s. Harris)
Harris Criterion (random $T_c$)

- Variation of average local $T_c$ in volume $\xi^d$

If true, inhomogeneity vanish at large length scales
Harris Criterion (random $T_c$)

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$$\Delta \langle T_c(x) \rangle \sim \xi^{-d/2}$$

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- Variation of average local $T_c$ in volume $\xi^d$
  \[ \Delta \langle T_c(x) \rangle \sim \xi^{-d/2} \]

- "Distance" from global $T_c$ in volume $\xi^d$
  \[ t \sim \xi^{-1/\nu} \]

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- "Distance" from global $T_c$ in volume $\xi^d$
  \[ t \sim \xi^{-1/\nu} \]

- Harris criterion
  \[ \Delta \langle T_c(x) \rangle < t \iff d\nu > 2 \]
  If true, inhomogeneity vanish at large length scales
Harris Criterion (random $T_c$)

- Variation of average local $T_c$ in volume $\xi^d$
  \[ \Delta \langle T_c(x) \rangle \sim \xi^{-d/2} \]

- “Distance” from global $T_c$ in volume $\xi^d$
  \[ t \sim \xi^{-1/\nu} \]

- Harris criterion
  \[ \Delta \langle T_c(x) \rangle < t \quad \Leftrightarrow \quad d\nu > 2 \quad \text{about clean CP.} \]
  If true, inhomogeneity vanish at large length scales.
Imry-Ma argument (random field)

- Random field breaks the order parameter symmetry
- Domains are pinned by the local fields
- Transition is rounded for $d \leq 2$
- At $d=2$ (lower critical dimension), domains are exponentially large
Know your OP and the types of disorder
Nematic QPT in cuprates?
Theory of the nodal nematic quantum phase transition in superconductors

Eun-Ah Kim,1 Michael J. Lawler,2 Paul Oreto,1 Subir Sachdev,3 Eduardo Fradkin,3 and Steven A. Kivelson1

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Nodal nematic QCP
deep inside d-wave SC
Nematic QCP, license to exist?

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nematic QCP inside SC phase?
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**Physical Review B 77, 184514 (2008)**

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- **Nodal nematic QCP** deep inside d-wave SC
- **Nematic d-SC:**
  - d-SC + small s-component
  \[ \Delta_d (\cos k_x - \cos k_y) + \lambda \phi \]
- Nematic QCP inside SC phase?
Looking for nematic critical fluctuations

- **Self energy** $\Sigma(\vec{q}, \omega)$ **due to fluctuation**

  **$k$-selective decoherence**

Interference of nematic quantum critical quasiparticles: a route to the octet model

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$^2$Department of Physics, Binghamton University, Binghamton NY 13902

(Dated: November 13, 2008)

arXiv:0811.2242

$\Sigma\psi_i(\vec{q}, \omega) = \tau_1 \quad k \quad k-q \quad \tau_1$

QPI peaks
BSCCO, got nematic?
Acknowledgements

Prof. Michael Lawler  
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Cornell

Dr. Andy Schmit  
Cornell

Prof. Seamus Davis  
Cornell, BNL
**Local measure of broken symmetry?**

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**dI/dV(ω)-map**
0D T_c=86K (p= )

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**R-map**
UD T_c=45K (p=0.08)

---

**Z-map(ω)**
UD T_c=45K

---

**Figure S7 a-f.** A series of images displaying the real space conductance ratio Z as a function of energy rescaled to the local psuedogap value, e = E/Δ_i(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 = Δ_i(r).
Piet Mondrian, 1915. Says he is searching for hidden order in nature...
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 (S. Chakravarty’s perspectives Science 08)

**Challenge:** An objective measure

UD $T_c=45K$ (p=0.08)  Kohsaka et al, Nature 454, 1072 (2008)
Local measure of broken symmetry?

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M. Lawler et al, in prep.

Challenge: An objective measure
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
On the shoulder of

- Relating asymmetry to a quantitative measure
  \[ Z(r, w) R(r) \]
  
  P. Anderson, N.P. Ong
  M.B.J. Meinders, H. Eskes, G.A. Sawatzky
  M. Randeria et al,
  PRL 95, 137001 (2005)

- Fourier filtering to look for stripe

  \[ N_f(r, E) = \int dr' f(r - r') N(r', E), \]
  \[ f(r) \propto \Lambda^2 e^{-r^2/\Lambda^2} \left[ \cos(\pi x/2a) + \cos(\pi y/2a) \right]. \]
  
  S. Kivelson et al,
  RMP 75, 1201 (2003)
Local measure of broken symmetry?

Z-map intensity at E = 150.0meV
Local measure of broken symmetry?
Local measure of broken symmetry?
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Local measure of broken symmetry?

Z-map intensity at $E = 150.0\text{meV}$

$Q_x$ vs $Q_y$?

$S_x$ vs $S_y$
Listen to Bragg Peaks
• Bragg peak

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

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

• Need O sites

\[ \tilde{Z}(\tilde{Q}_x) = \tilde{Z}_{Cu} - \tilde{Z}_{Ox} + \tilde{Z}_{Oy}, \quad \tilde{Z}(\tilde{Q}_y) = \tilde{Z}_{Cu} + \tilde{Z}_{Ox} - \tilde{Z}_{Oy} \]

\[ \mathcal{O}_N \propto (\tilde{Z}_{Ox} - \tilde{Z}_{Oy}) \]
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**Q_1 vs Q_2**

- **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**
  \[ O_N \equiv \frac{[\tilde{Z}(\tilde{Q}_x) - \tilde{Z}(\tilde{Q}_y) + \tilde{Z}(-\tilde{Q}_x) - \tilde{Z}(-\tilde{Q}_y)]}{(\text{sum})} \]

- **Need O sites**
  \[ \tilde{Z}(\tilde{Q}_x) = \tilde{Z}_{Cu} - \tilde{Z}_{Ox} + \tilde{Z}_{Oy}, \quad \tilde{Z}(\tilde{Q}_y) = \tilde{Z}_{Cu} + \tilde{Z}_{Ox} - \tilde{Z}_{Oy} \]
  \[ O_N \propto (\tilde{Z}_{Ox} - \tilde{Z}_{Oy}) \]
**Q₁ vs Q₂**

- **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**
  \[
  O_N \equiv \frac{[\tilde{Z}(\vec{Q}_x) - \tilde{Z}(\vec{Q}_y) + \tilde{Z}(\vec{Q}_x) - \tilde{Z}(\vec{Q}_y)]}{(\text{sum})}
  \]

  \(\Rightarrow\) **Measure C₄ breaking**

- **Need O sites**
  \[
  \tilde{Z}(\vec{Q}_x) = \tilde{Z}_{Cu} - \tilde{Z}_{Ox} + \tilde{Z}_{Oy}, \quad \tilde{Z}(\vec{Q}_y) = \tilde{Z}_{Cu} + \tilde{Z}_{Ox} - \tilde{Z}_{Oy}
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\[ O_N \equiv \frac{[\tilde{Z}(\tilde{Q}_x) - \tilde{Z}(\tilde{Q}_y) + \tilde{Z}(-\tilde{Q}_x) - \tilde{Z}(-\tilde{Q}_y)]}{(sum)} \]

\[ \Rightarrow \text{Measure C}_4 \text{ breaking} \]

- Nematic OP

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

\[ O_N \propto (\tilde{Z}_{O_x} - \tilde{Z}_{O_y}) \]

V. Emery, PRL 58, 2974 (1987)
Nematic ordering in UD 45

\[ O_N \equiv \left[ \tilde{Z}(Q_x) - \tilde{Z}(Q_y) + \tilde{Z}(-Q_x) - \tilde{Z}(-Q_y) \right] / \text{sum} \]

Extracted from published data, T=4K

Domain size in Z-map
Domain size in Z-map

Z-map intensity at $E = 6.0\,\text{meV}$
Nematic domains

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

- Shift $Q_x$, $Q_y$ to origin ("tune to the channel")

- Low pass filter (long distance physics)
Listen to channel S
Oriented stripe domains

- Shift $S_x$, $S_y$ to origin ("tune to the channel")

- Low pass filter (long distance physics)
Hypothesis: longer ranged orientational ordering than stripe 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)
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Electronic Nematic in Cuprates?

Looking ahead

• Doping dependence?
• Temperature dependence?
• Diffraction measurements?

‣ Phenomenological model

‣ Why would cuprates do that?

‣ Is it useful for superconductivity?