The Role of Charge Order in the Mechanism of High Temperature Superconductivity

Eduardo Fradkin

Department of Physics

University of Illinois at Urbana-Champaign

Collaborators

Steven Kivelson, UCLA/Stanford

Enrico Arrigoni, Technische Universität Graz, Austria

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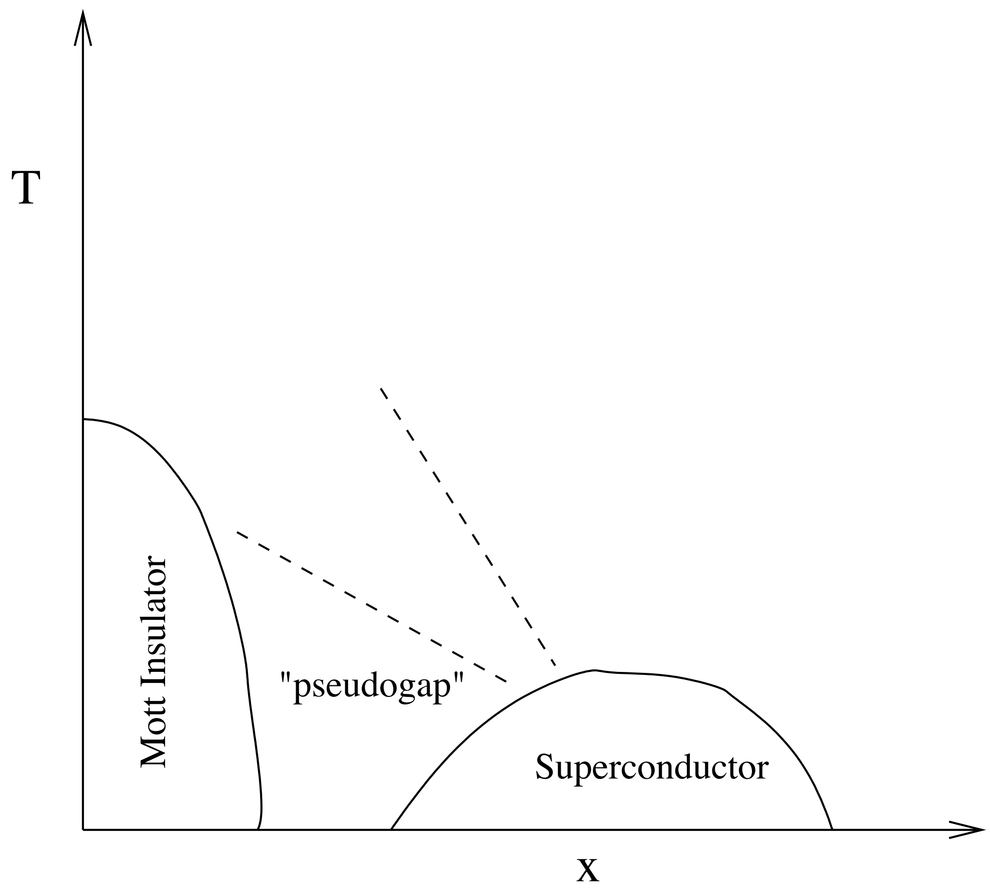
Outline

- Inhomogeneous Phases are inherent to Doped Mott Insulators
- Charge Order and Superconductivity: friend or foe?
- High T_c Superconductivity in a Striped Hubbard Model
- Isolated doped Hubbard Ladders as the prototype spin-gap systems
- Estimating T_c: How high is high?
- Conclusions and Open Questions

Punch Line

- Long held belief: charge order competes and suppresses superconductivity
- Electronic liquid crystal phases, not only can coexist with superconductivity but can also provide a mechanism for high T_c superconductivity.
- Inhomogeneous phases: natural local pairing mechanism with purely repulsive interactions
- This mechanism is not due to an infinitesimal instability
- Underlying normal state is not a Fermi liquid and it does not have quasiparticles
- T_c scales like a simple power of a coupling instead of an exponential dependence

Phase Diagram of the High T_c Superconductors



What do experiments tell us

- Evidence for stripe charge order in underdoped high temperature superconductors (LSCO, non-SC LBCO and YBCO) (Tranquada, Ando, Mook)
- Evidence of coexistence of *fluctuating* stripe charge order and superconductivity in LSCO and YBCO (Mook, Tranquada)
- Similarity of high energy neutron spectra in LSCO, non-SC LBaCO, YBCO and the ladder system (Tranquada, Mook, Keimer, Buyers)
- Evidence of induced charge order in the SC phase in vortex halos: neutrons in LSCO (B. Lake), STM in BSCCO (Davis)
- STM Experiments: short range stripe order (on scales long compared to ξ_0), possible broken rotational symmetry (BSCCO and NaCCOC) (Kapitulnik, Davis, Yazdani)
- Transport experiments give evidence for charge domain switching in YBCO wires (Van Harlingen and Weissmann) and hysteretic effects in the “normal state” of LSCO (Panagopoulos)

Electron Liquid Crystal Phases

S. Kivelson, E. Fradkin, V. Emery, Nature **393**, 550 (1998)

Doping a Mott insulator: inhomogeneous phases arise due to the competition between phase separation and strong correlations

- Crystal Phases: break all continuous translation symmetries and rotations
- Smectic (Stripe) phases: break one translation symmetry and rotations
- Nematic and Hexatic Phases: are uniform and anisotropic
- Uniform fluids: break no spatial symmetries

High T_c Superconductors : Lattice effects $\Rightarrow$ breaking of point group symmetries

If lattice effects are weak (high T) $\Rightarrow$ continuous symmetries essentially recovered

2DEG in GaAs heterostructures $\Rightarrow$ continuous symmetries

Electronic Liquid Crystal Phases in High T_c Superconductors

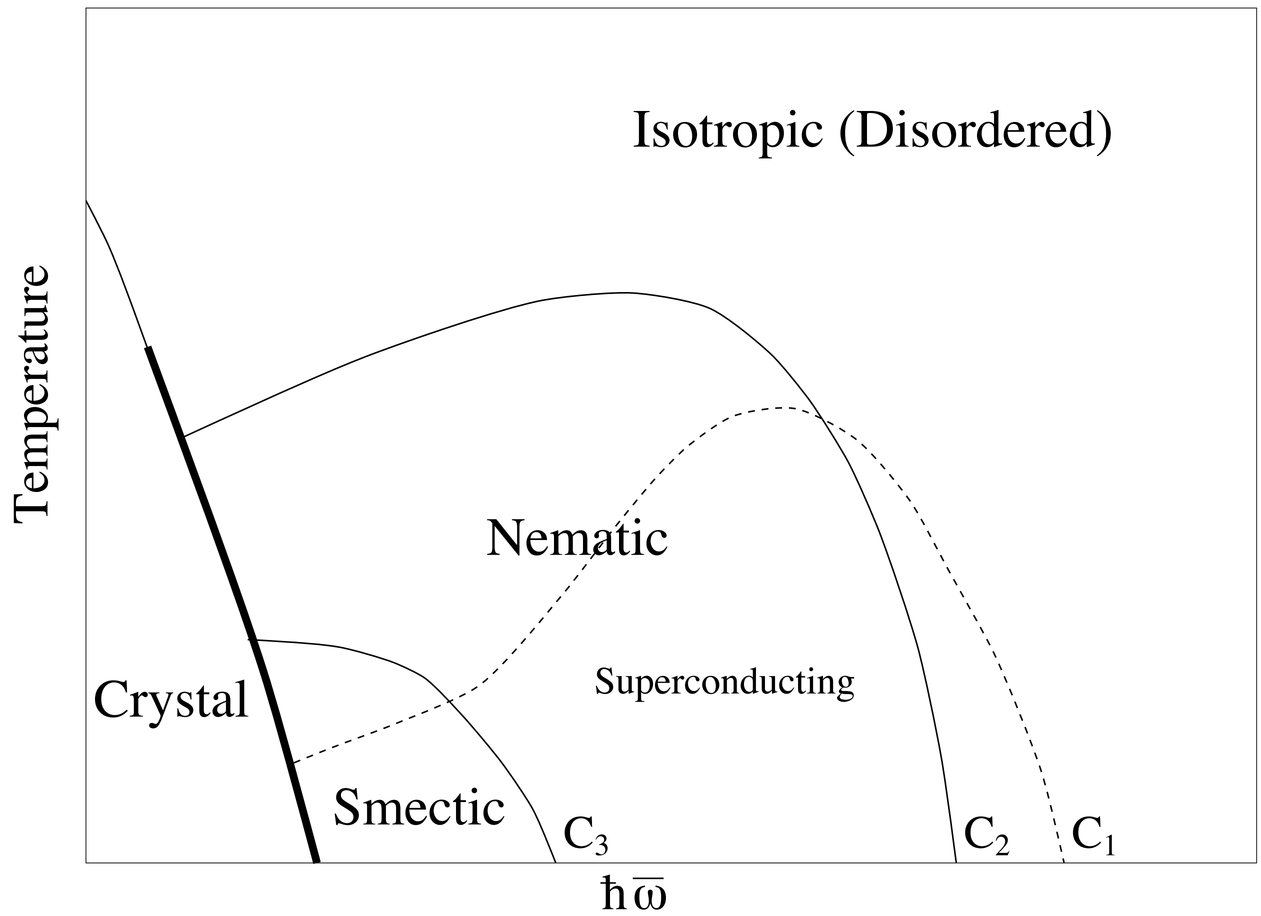
- Liquid: Isotropic, breaks no spacial symmetries; either a conductor or a superconductor
- Nematic: Lattice effects reduce the symmetry to a rotations by $\pi/2$ ("Ising"); translation and reflection symmetries are unbroken; it is an anisotropic liquid with a preferred axis
- Smectic: breaks translation symmetry only in one direction but liquid-like on the other; Stripe phase; (infinite) anisotropy of conductivity tensor
- Crystal(s): electron solids ("CDW"); insulating states.

Soft Quantum Matter

or

Quantum Soft Matter

Schematic Phase Diagram of Doped Mott Insulators



Order Parameters for the Smectic (Stripe) State

- Two-dimensionally ordered state with unidirectional CDW order
- charge modulation $\Rightarrow$ charge stripe
- if it coexists with spin order $\Rightarrow$ spin stripe
- stripe state $\Rightarrow$ new Bragg peaks of the electron density at

$$\vec{k} = \pm \vec{Q}_{\text{ch}} = \pm \frac{2\pi}{\lambda_{\text{ch}}} \hat{e}_x$$

- spin stripe $\Rightarrow$ magnetic Bragg peaks at

$$\vec{k} = \vec{Q}_s = (\pi, \pi) \pm \frac{1}{2} \vec{Q}_{\text{ch}}$$

- Order Parameter: $\langle n_{\vec{Q}_{\text{ch}}} \rangle$, Fourier component of the electron density at $\vec{Q}_{\text{ch}}$.

Stripe Phases and the Mechanism of high T_c superconductivity in Strongly Correlated Systems

Since the discovery of high T_c superconductivity it has been clear that

- High T_c Superconductors are never normal metals and don't have well defined quasiparticles in the "normal state" (linear resistivity, ARPES)
- the "parent compounds" are strongly correlated Mott insulators
- repulsive interactions dominate
- whatever "the mechanism" is has to account for these facts

Problem

BCS is so successful in conventional metals that the term mechanism naturally evokes the idea of a weak coupling instability with (write here your favorite boson) mediating an attractive interaction between well defined quasiparticles.

Superconductivity in a Doped Mott Insulator

or

How To Get Pairing from Repulsive Interactions

- Universal assumption: 2D Hubbard-like models should contain the essential physics
- "RVB" mechanism:
  - Mott insulator: spins are bound in singlet valence bonds; it is a strongly correlated spin liquid, essentially a pre-paired insulating state
  - spin-charge separation in the doped state leads to high T_c superconductivity

Problems

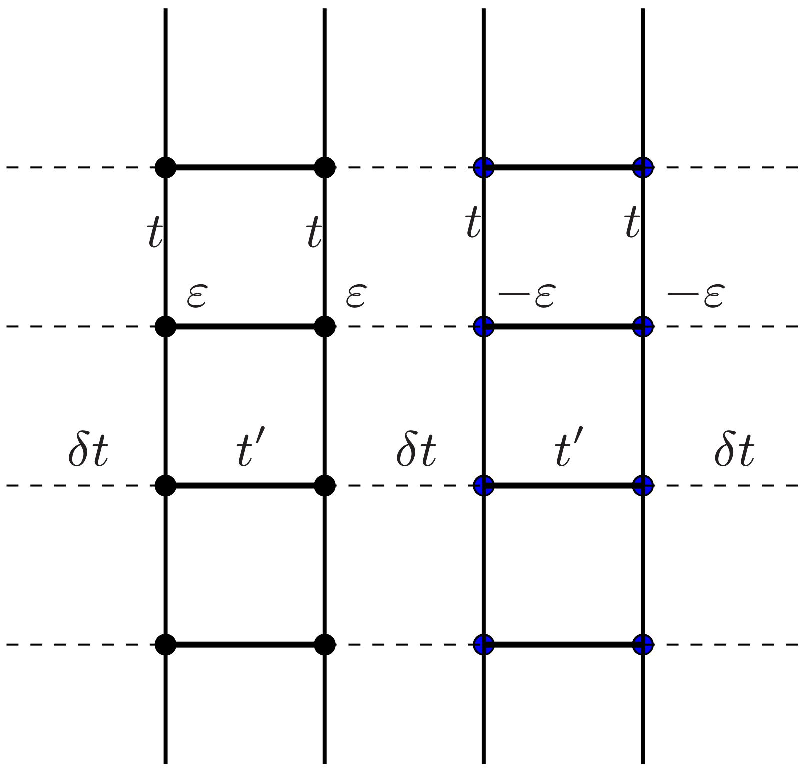
- there is no real evidence that the simple 2D Hubbard model favors superconductivity (let alone high T_c superconductivity)
- all evidence indicates that if anything it wants to be an insulator and to phase separate (finite size diagonalizations, various Monte Carlo simulations)
- strong tendency for the ground states to be inhomogeneous and possibly anisotropic
- no evidence (yet) for a spin liquid in 2D Hubbard-type models

Why an Inhomogeneous State is Good for high T_c superconductivity

Stripe Hubbard Model

A Cartoon of the Strongly Correlated Stripe Phase

$$H = -\sum_{<\vec{r},\vec{r}'>,\sigma} t_{\vec{r},\vec{r}'} \left[c^\dagger_{\vec{r},\sigma} c_{\vec{r}',\sigma} + \text{h.c.} \right] + \sum_{\vec{r},\sigma} \left[\epsilon_{\vec{r}}\, c^\dagger_{\vec{r},\sigma} c_{\vec{r},\sigma} + \frac{U}{2} c^\dagger_{\vec{r},\sigma} c^\dagger_{\vec{r},-\sigma} c_{\vec{r},-\sigma} c_{\vec{r},\sigma} \right]$$



Physics of the 2-leg ladder

White, Affleck and Scalapino; Noack, White and Scalapino; Siller, Troyer and Rice; Balents and Fisher; Dagotto and Rice; Emery, Kivelson and Zachar; Wu, Liu and Fradkin

We will consider first an isolated 2-leg ladder: here we set $\delta t = 0$

- At $x = 0$ there is a unique fully gapped ground state ("$C0S0$"); for $U \gg t$, $\Delta_s \sim J/2$
- For $0 < x < x_c \sim 0.3$, Luther-Emery liquid: no charge gap and large spin gap ("$C1S0$"); spin gap $\Delta_s \downarrow$ as $x \uparrow$, and $\Delta_s \to 0$ as $x \to x_c$
- Effective Hamiltonian for the charge degrees of freedom

$$H = \int dy \frac{v_c}{2} \left[K \left(\partial_y \theta \right)^2 + \frac{1}{K} \left(\partial_x \phi \right)^2 \right] + \ldots$$

  ϕ: CDW phase field; θ: SC phase field; $[\phi(y'), \partial_y \theta(y)] = i\delta(y - y')$

- x-dependence of Δ_s, K, v_c, and μ depends on t'/t and U/t
- $\ldots$ represent cosine potentials: Mott gap Δ_M at $x = 0$
- Excitations for $x \to 0$ are spinless charge $2e$ fermionic solitons

- $K \to 2$ as $x \to 0$; $K \sim 1$ for $x \sim 0.1$, and $K \sim 1/2$ for $x \sim x_c$
- $\chi_{\rm SC} \sim \Delta_s / T^{2-K^{-1}}$ $\qquad \chi_{\rm CDW} \sim \Delta_s / T^{2-K}$
- $\chi_{\rm CDW}(T) \to \infty$ and $\chi_{\rm SC}(T) \to \infty$ for $0 < x < x_c$
- For $x \lesssim 0.1$, $\chi_{\rm SC} \gg \chi_{\rm CDW}$!
- Electron ($P = 2\pi x$)

$$\Psi^{\dagger}_{\pm,\sigma} \sim \exp\left(i\sqrt{\pi/2}\,[\theta \pm \phi + \sigma\theta_s \pm \sigma\phi_s] \pm iPy/2\right)$$

CDW

$$\widehat{\rho}_P = \sum_{\sigma} \Psi^{\dagger}_{L,\sigma}\Psi_{R,\sigma} \propto \exp(iPy + i\sqrt{2\pi}\phi)$$

SC

$$\widehat{\Phi} = \Psi^{\dagger}_{L,\uparrow}\Psi^{\dagger}_{R,\downarrow} + \Psi^{\dagger}_{R,\uparrow}\Psi^{\dagger}_{L,\downarrow} \propto \exp\left(1\sqrt{2\pi}\theta\right)$$

Effects of Inter-ladder Couplings

- In the Luther-Emery phase, $0 < x < x_c$, there is a spin gap and single particle tunneling is irrelevant
- Second order processes in δt:
  - marginal (and small) forward scattering inter-ladder interactions
  - Josephson couplings, possibly relevant
  - CDW couplings, possibly relevant
- Relevant Perturbations

$$H' = -\sum_J \int dy \left[\mathcal{J} \cos\left(\sqrt{2\pi}\Delta\theta_J)\right) + \mathcal{V} \cos\left(\Delta P_J y + \sqrt{2\pi}\Delta\phi_J)\right)\right]$$

J: ladder index; $P_J = 2\pi x_J$, $\Delta\phi_J = \phi_{J+1} - \phi_J$, etc.

- $\mathcal{J}$ and $\mathcal{V}$ are effective couplings which must be computed from microscopics
- Estimate: $\mathcal{J} \approx \mathcal{V} \propto (\delta t)^2 / J$

Period 2 works for $x \ll 1$

- If all the ladders are equivalent, a period 2 stripe ordered or column state
- For an isolated ladder $T_c = 0$
- $\mathcal{J} \neq 0$ and $\mathcal{V} \neq 0$, $T_C > 0$
- For $x \lesssim 0.1$ CDW couplings are irrelevant $(1 < K < 2)$: Inter-ladder Josephson coupling leads to a superconducting state in a restricted range of small x with rather low T_c.

$$2\mathcal{J}\chi_{\mathrm{SC}}(T_c) = 1$$

- $T_c \propto \delta t x$
- For larger x, $K < 1$ and χ_{CDW} is more strongly divergent than χ_{SC}
- CDW couplings become more relevant $\Rightarrow$ Insulating, incommensurate CDW state with ordering wave number $P = 2\pi x$.

Why Period 4 works!

- Consider an alternating array of A and B type ladders (with different electron affinities) in the LE regime
- SC T_c:
$$(2\mathcal{J})^2\chi_{\rm SC}^A(T_c)\chi_{\rm SC}^B(T_c) = 1$$
- CDW T_c:
$$(2\mathcal{V})^2\chi_{\rm CDW}^A(P,T_c)\chi_{\rm CDW}^B(P,T_c) = 1$$
- 2D CDW order is greatly suppressed due to the mismatch between ordering vectors, P_A and P_B, on neighboring ladders
- For inequivalent ladders SC beats CDW if
$$2 > K_A^{-1} + K_B^{-1} - K_A; \quad 2 > K_A^{-1} + K_B^{-1} - K_B$$
-
$$T_c \sim \Delta_s \left(\frac{\mathcal{J}}{\widetilde{W}}\right)^\alpha; \; \alpha = \frac{2K_AK_B}{[4K_AK_B - K_A - K_B]}$$
- $\mathcal{J} \sim \delta t^2/J$ and $\widetilde{W} \sim J$; T_c is (power law) small for small $\mathcal{J}$! ($\alpha \sim 1$).

How reliable are these estimates?

- This is a mean-field estimate for T_c and it is an upper bound to the actual T_c.
- T_c should be suppressed by phase fluctuations by up to a factor of 2.
- Indeed, perturbative RG studies for small $\mathcal{J}$ yield the same power law dependence. This result is asymptotically exact for $\mathcal{J} << \widetilde{W}$.
- Since T_c is a smooth function of $\delta t/\mathcal{J}$, it is reasonable to extrapolate for $\delta t \sim \mathcal{J}$.
- $\Rightarrow$ $T_c^{\max} \propto \Delta_s$ $\Rightarrow$high T_c.
- This is in contrast to the exponentially small T_c as obtained in a BCS-like mechanism.

Conclusions and Open Questions

- a period 2 modulation can produce superconductivity with a relatively low T_c in a restricted doping range,
- a period 4 modulation produces higher critical temperatures on a broader range of doping.
- T_c is only power-law small, with $\alpha \sim 1$
- no exponential suppression of $T_c \Rightarrow$ "high T_c"
- This model is cartoon of the symmetry breaking of stripe (smectic) state
- It has a large spin gap and it does not have low-energy spin fluctuations
- the order-parameter is d-wave like: it changes sign under $\pi/2$ rotations
- It does not have nodal fermionic excitations
- Nodal fermions may appear upon a Lifshitz transition at larger x