A theory of the underdoped cuprates

Talk online: sachdev.physics.harvard.edu
A theory of the underdoped cuprates


Paired electron pockets in the underdoped cuprates, V. Galitski and S. Sachdev, arXiv:0901.0005
Outline

1. Nodal-anti-nodal dichotomy in the cuprates
   Survey of recent experiments

2. Spin density wave theory of normal metal
   From a “large” Fermi surface to electron and hole pockets

3. Loss of Neel order in insulating square lattice antiferromagnets
   Landau-Ginzburg theory vs. gauge theory for spinons

4. Algebraic charge liquids
   Pairing by gauge forces, d-wave superconductivity, and the nodal-anti-nodal dichotomy
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The cuprate superconductors
Near $p \sim 20\%$ -- electronic structure consistent with d-BCS
Near p~ 20% -- electronic structure consistent with d-BCS.
Normal State k-Space Electronic Structure

Parameterization:
M. Norman

Based on data:
Ding et al.,
SC State: Momentum-dependent Pair Energy Gap $\Delta(\vec{k})$

The SC energy gap $\Delta(\vec{k})$ has four nodes.

- Shen et al, PRL 70, 3999 (1993)
- Ding et al, PRB 54, 9678 (1996)
Pseudogap: Temperature-independent energy gap exists $T \gg T_c$

Ch. Renner et al, PRL 80, 149 (1998)
Ø. Fischer et al, RMP 79, 353 (2007)
Pseudogap: Temperature-independent energy gap near $k \sim (\pi,0)$

Pseudogap: Temperature-dependent energy gap near node

Nodal-anti-nodal dichotomy in the underdoped cuprates


**Figure 2.** Pseudogap ($E_{pg} = 2\Delta_{pg}$) and superconducting ($E_{sc} \sim 5k_B T_c$) energy scales for a number of HTSCs with $T_{max} \sim 95$ K (Bi2212, Y123, Ti2201 and Hg1201). The datapoints were obtained, as a function of hole doping $x$, by angle-resolved photoemission spectroscopy (ARPES), tunneling (STM, SIN, SIS), Andreev reflection (AR), Raman scattering (RS) and heat conductivity (HC). On the same plot we are also including the energy $\Omega_c$ of the magnetic resonance mode measured by inelastic neutron scattering (INS), which we identify with $E_{sc}$ because of the striking quantitative correspondence as a function of $T_c$. The data fall on two universal curves given by $E_{pg} = E_{pg}^{max}(0.27 - x)/0.22$ and $E_{sc} = E_{sc}^{max}[1 - 82.6(0.16 - x)^2]$, with $E_{pg}^{max} = E_{pg}(x = 0.05) = 152 \pm 8$ meV and $E_{sc}^{max} = E_{sc}(x = 0.16) = 42 \pm 2$ meV (the statistical errors refer to the fit of the selected datapoints; however, the spread of all available data would be more appropriately described by $\pm 20$ and $\pm 10$ meV, respectively).
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Spin density wave theory in hole-doped cuprates

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Spin density wave theory in hole-doped cuprates

Increasing SDW order

\[ \vec{\phi} \]

\[ O(3) \text{ vector order parameter } \vec{\phi} \]

Spin density wave theory in electron-doped cuprates

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Increasing SDW order

$\vec{\phi}$

$O(3)$ vector order parameter $\vec{\phi}$

Photoemission in NCCO (electron-doped)

Quantum oscillations and the Fermi surface in an underdoped high $T_c$ superconductor (ortho-II ordered $\text{YBa}_2\text{Cu}_3\text{O}_{6.5}$).

Electron pockets in the Fermi surface of hole-doped high-\(T_c\) superconductors

David LeBoeuf\(^1\), Nicolas Doiron-Leyraud\(^1\), Julien Levallois\(^2\), R. Daou\(^1\), J.-B. Bonnemaison\(^1\), N. E. Hussey\(^3\), L. Balicas\(^4\), B. J. Ramshaw\(^5\), Ruixing Liang\(^5,6\), D. A. Bonn\(^5,6\), W. N. Hardy\(^5,6\), S. Adachi\(^7\), Cyril Proust\(^2\) & Louis Taillefer\(^{1,6}\)

_Nature_ 450, 533 (2007)
Spin density wave theory in hole-doped cuprates

Increasing SDW order

$O(3)$ vector order parameter $\vec{\phi}$
Spin density wave theory in hole-doped cuprates

- Loss of SDW order coincides with large Fermi surface to electron/hole pocket transition.

- Landau-Ginzburg-Hertz theory for SDW ordering:

\[
S_H = \int d^2r d\tau \left\{ \frac{1}{2}(\nabla \varphi)^2 + \frac{s}{2} \varphi^2 + \frac{u}{2} \left( \varphi^2 \right)^2 \right\} + \int \frac{d^2k d\omega}{8\pi^3} |\omega||\varphi(k, \omega)|^2
\]
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Square lattice antiferromagnet

\[ H = \sum_{\langle ij \rangle} J_{ij} \vec{S}_i \cdot \vec{S}_j \]

Ground state has long-range Néel order

Order parameter is a single vector field \( \vec{\varphi} = \eta_i \vec{S}_i \)

\( \eta_i = \pm 1 \) on two sublattices

\( \langle \vec{\varphi} \rangle \neq 0 \) in Néel state.
Square lattice antiferromagnet

\[ H = \sum_{\langle ij \rangle} J_{ij} \vec{S}_i \cdot \vec{S}_j \]

Weaken some bonds to induce spin entanglement in a new quantum phase
Quantum critical point with non-local entanglement in spin wavefunction

\[ \lambda \]

**O(3) vector order parameter** \( \vec{\phi} \)

\[ S_{LG} = \int d^2r d\tau \left[ (\partial_\tau \vec{\phi})^2 + c^2 (\nabla_r \vec{\phi})^2 + s \vec{\phi}^2 + u (\vec{\phi}^2)^2 \right] \]

CFT3

\[ = \frac{1}{\sqrt{2}} \left( \left| \uparrow \downarrow \right\rangle - \left| \downarrow \uparrow \right\rangle \right) \]
Square lattice antiferromagnet

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\( \langle \vec{\varphi} \rangle \neq 0 \) in Néel state.
Square lattice antiferromagnet

$$H = \sum_{\langle ij \rangle} J_{ij} \vec{S}_i \cdot \vec{S}_j$$

Destroy Neel order by perturbations which preserve full square lattice symmetry e.g. second-neighbor or ring exchange.

What are possible states with $\langle \vec{\varphi} \rangle = 0$?
Square lattice antiferromagnet

\[ H = \sum_{\langle ij \rangle} J_{ij} \vec{S}_i \cdot \vec{S}_j \]

What are possible states with \( \langle \vec{\phi} \rangle = 0 \) ?

Destroy Neel order by perturbations which preserve full square lattice symmetry e.g. second-neighbor or ring exchange.
Theory for loss of Neel order

Write the Néel order in terms of Schwinger bosons (spinons) $z_{i\alpha}$, $\alpha = \uparrow, \downarrow$ :

$$\vec{\varphi}_i = z_i^{\dagger} \vec{\sigma}_{\alpha\beta} z_i^{\beta}$$

where $\vec{\sigma}$ are Pauli matrices, and the bosons obey the local constraint

$$\sum_{\alpha} z_i^{\dagger} z_i^{\alpha} = 2S$$

Effective theory for spinons must be invariant under the U(1) gauge transformation

$$z_{i\alpha} \rightarrow e^{i\theta} z_{i\alpha}$$
Perturbation theory

Low energy spinon theory for “quantum disordering” the Néel state is the $\text{CP}^1$ model

$$S_z = \int d^2 x d\tau \left[ c^2 |(\nabla_x - iA_x)z_{\alpha}|^2 + |(\partial_\tau - iA_\tau)z_{\alpha}|^2 + s |z_{\alpha}|^2 ight. \\
+ u (|z_{\alpha}|^2)^2 + \left. \frac{1}{4e^2} (\epsilon_{\mu\nu\lambda} \partial_\nu A_\lambda)^2 \right]$$

where $A_\mu$ is an emergent $\text{U}(1)$ gauge field which describes low-lying spin-singlet excitations.

Phases:

$\langle z_{\alpha} \rangle \neq 0 \Rightarrow$ Néel (Higgs) state

$\langle z_{\alpha} \rangle = 0 \Rightarrow$ Spin liquid (Coulomb) state
Perturbation theory

Low energy spinon theory for “quantum disordering” the Néel state is the $\text{CP}^1$ model

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Phases:

$$\langle z_\alpha \rangle \neq 0 \implies \text{Néel (Higgs) state}$$

$$\langle z_\alpha \rangle = 0 \implies \text{Spin liquid (Coulomb) state}$$

Distinct universality from $\text{O}(3)$ model

Quantum “disordering” magnetic order

Spin liquid with a “photon”, which is unstable to the appearance of valence bond solid (VBS) order

collinear Néel state

Order parameter of VBS state

\[ \Psi_{\text{vbs}}(i) = \sum_{\langle ij \rangle} \vec{S}_i \cdot \vec{S}_j e^{i \arctan(\mathbf{r}_j - \mathbf{r}_i)} \]
Order parameter of VBS state

\[ \Psi_{\text{vbs}}(i) = \sum_{\langle ij \rangle} \vec{S}_i \cdot \vec{S}_j e^{i \arctan(r_j - r_i)} \]
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Order parameter of VBS state

\[ \Psi_{vbs}(i) = \sum_{\langle ij \rangle} \vec{S}_i \cdot \vec{S}_j e^{i \arctan(r_j - r_i)} \]
The order parameter of the VBS state is given by:

\[
\Psi_{\text{vbs}}(i) = \sum_{\langle ij \rangle} \langle \vec{S}_i \cdot \vec{S}_j \rangle e^{i \arctan(r_j - r_i)}
\]
Order parameter of VBS state

\[ \Psi_{\text{vbs}}(i) = \sum_{\langle ij \rangle} \vec{S}_i \cdot \vec{S}_j e^{i \arctan(\mathbf{r}_j - \mathbf{r}_i)} \]
Near the Néel-VBS transition, the (nearly) gapless photon can be identified with the Goldstone mode associated with an emergent circular symmetry

$$\Psi_{\text{vbs}} \rightarrow \Psi_{\text{vbs}} e^{i\theta}.$$
Quantum Monte Carlo simulations display convincing evidence for a transition from a Neel state at small $Q$ to a VBS state at large $Q$.

\[ \mathcal{H}_{\text{SU}(2)} = J \sum_{\langle ij \rangle} \mathbf{S}_i \cdot \mathbf{S}_j - Q \sum_{\langle ijkl \rangle} (\mathbf{S}_i \cdot \mathbf{S}_j - \frac{1}{4}) (\mathbf{S}_k \cdot \mathbf{S}_l - \frac{1}{4}) \]

Emergent circular symmetry is evidence for $U(1)$ photon and topological order

$\mathcal{H}_{\text{SU}(2)} = J \sum_{\langle ij \rangle} \mathbf{S}_i \cdot \mathbf{S}_j - Q \sum_{\langle i j k l \rangle} \left( \mathbf{S}_i \cdot \mathbf{S}_j - \frac{1}{4} \right) \left( \mathbf{S}_k \cdot \mathbf{S}_l - \frac{1}{4} \right)$

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Spin density wave theory in hole-doped cuprates

Increasing SDW order

$O(3)$ vector order parameter $\vec{\varphi}$
Spinon theory in hole-doped cuprates

SU(2) spinor order parameter $z_\alpha$
Charge carriers in the lightly-doped cuprates with Neel order

Electron pockets

Hole pockets
Begin with the representation of the antiferromagnet as a CP$^1$ model (where $z^*_\alpha \bar{\sigma}_{\alpha\beta} z_\beta$ is the Néel order parameter, and $A_\mu$ is an emergent gauge field):

$$\mathcal{L}_z = |(\partial_\mu - iA_\mu) z_\alpha|^2 + s|z_\alpha|^2 + \frac{u}{2} (|z_\alpha|^2)^2.$$
• Begin with the representation of the antiferromagnet as a CP$^1$ model (where $z^*_\alpha \tilde{\sigma}_{\alpha \beta} z_\beta$ is the Néel order parameter, and $A_\mu$ is an emergent gauge field):

$$\mathcal{L}_z = |(\partial_\mu - i A_\mu) z_\alpha|^2 + s |z_\alpha|^2 + \frac{u}{2} (|z_\alpha|^2)^2.$$ 

We have the conventional SDW metal for $s < 0$ where $z_\alpha$ condense.
For $s > 0$ there is no SDW order, but “ghosts” of electron/hole pockets survive in an algebraic charge liquid.
Write the electron operator at wavevector $Q_1$ in terms of fermions $g_\pm$ polarized along the local direction of the SDW order:

\[
\begin{pmatrix}
c_{\uparrow}(Q_1) \\
c_{\downarrow}(Q_1)
\end{pmatrix}
= \begin{pmatrix}
z_{\uparrow} & -z^*_{\downarrow} \\
z_{\downarrow} & z^*_{\uparrow}
\end{pmatrix}
\begin{pmatrix}
g_+ \\
g_-
\end{pmatrix}.
\]

Electron pocket is polarized in a *rotating reference frame* defined by the local SDW order.
This is linked to the electron operator at the pocket at $Q_2$ separated by the SDW ordering wavevector:

$$\left( \begin{array}{c} c_{\uparrow}(Q_2) \\ c_{\downarrow}(Q_2) \end{array} \right) = \left( \begin{array}{cc} z_{\uparrow} & z^*_{\downarrow} \\ z_{\downarrow} & -z^*_{\uparrow} \end{array} \right) \left( \begin{array}{c} g_+ \\ g_- \end{array} \right).$$

Electron pocket is polarized in a *rotating reference frame* defined by the local SDW order.
Low energy theory for spinless, charge $-e$ fermions $g_{\pm}$:

$$\mathcal{L}_g = g_+^\dagger \left[ (\partial_\tau - iA_\tau) - \frac{1}{2m^*} (\nabla - iA)^2 - \mu \right] g_+$$

$$+ g_-^\dagger \left[ (\partial_\tau + iA_\tau) - \frac{1}{2m^*} (\nabla + iA)^2 - \mu \right] g_-$$

Two Fermi surfaces coupled to a fluctuating gauge field with opposite charges.
Strong pairing of the $g_{\pm}$ electron pockets

- Problem is similar to double layer quantum Hall systems at total filling fraction $\nu = 1$. At large layer spacing we have 2 composite fermion Fermi surfaces each at filling fraction $\nu = 1/2$. At small layer spacing, there is a paired state formed by attractive interaction mediated by antisymmetric gauge field.

Strong pairing of the $g_\pm$ electron pockets

- Problem is similar to double layer quantum Hall systems at total filling fraction $\nu = 1$. At large layer spacing we have 2 composite fermion Fermi surfaces each at filling fraction $\nu = 1/2$. At small layer spacing, there is a paired state formed by attractive interaction mediated by antisymmetric gauge field.

- Gauge forces lead to a $s$-wave paired state with a $T_c$ of order the Fermi energy of the pockets. Inelastic scattering from low energy gauge modes lead to very singular $g_\pm$ self energy, but is not pair-breaking.

$$\langle g_+ g_- \rangle = \Delta$$
Strong pairing of the $g_{\pm}$ electron pockets

- Transforming back to the physical fermions we find

$$\langle c_{\uparrow}(Q_1)c_{\downarrow}(Q_1) \rangle = -\langle c_{\uparrow}(Q_2)c_{\downarrow}(Q_2) \rangle \sim \Delta$$

i.e. the pairing signature for the electrons is $d$-wave.
Strong pairing of the $g_{\pm}$ electron pockets

- Transforming back to the physical fermions we find

$$\langle c_{\uparrow}(Q_1)c_{\downarrow}(Q_1) \rangle = -\langle c_{\uparrow}(Q_2)c_{\downarrow}(Q_2) \rangle \sim \Delta$$

i.e. the pairing signature for the electrons is $d$-wave.
Low energy theory for spinless, charge \( +e \) fermions \( f_{\pm v} \):

\[
\mathcal{L}_f = \sum_{v=1,2} \left\{ f_{+v}^\dagger \left[ (\partial_\tau - iA_\tau) - \frac{1}{2m^*}(\nabla - iA)^2 - \mu \right] f_{+v} \\
+ f_{-v}^\dagger \left[ (\partial_\tau + iA_\tau) - \frac{1}{2m^*}(\nabla + iA)^2 - \mu \right] f_{-v} \right\}
\]

Two pairs of Fermi surfaces coupled to a fluctuating gauge field with opposite charges
Weak pairing of the $f_{\pm}$ hole pockets

\[
\mathcal{L}_{\text{Josephson}} = i J_{fg} \left[ g_+ g_- \right] \left[ f_{+1} \vec{\partial}_x f_{-1} - f_{+1} \vec{\partial}_y f_{-1} \right. \\
\left. + f_{+2} \vec{\partial}_x f_{-2} + f_{+2} \vec{\partial}_y f_{-2} \right] + \text{H.c.}
\]


Proximity Josephson coupling to $g_{\pm}$ fermions leads to $p$-wave pairing of the $f_{\pm v}$ fermions. Gauge forces are strongly pair-breaking, and so the pairing is very weak.

\[
\langle f_{+1}(k)f_{-1}(-k) \rangle \sim (k_x - k_y) J_{fg} \Delta; \\
\langle f_{+2}(k)f_{-2}(-k) \rangle \sim (k_x + k_y) J_{fg} \Delta; \\
\langle f_{+1}(k)f_{-2}(-k) \rangle = 0,
\]
Increasing SDW order

Weak pairing of the $f_\pm$ hole pockets

$$\langle f_{+1}(k)f_{-1}(-k) \rangle \sim (k_x - k_y)J_{fg}\Delta;$$
$$\langle f_{+2}(k)f_{-2}(-k) \rangle \sim (k_x + k_y)J_{fg}\Delta;$$
$$\langle f_{+1}(k)f_{-2}(-k) \rangle = 0,$$
$d$-wave pairing of the electrons is associated with

- Strong $s$-wave pairing of $g_{\pm}$
- Weak $p$-wave pairing of $f_{\pm v}$.
Conclusions

★ Non-Landau-Ginzburg theory for loss of antiferromagnetic order in a metal

★ New metallic state has “ghost” electron and hole pockets

★ Natural route to $d$-wave pairing with strong pairing at the antinodes and weak pairing at the nodes
Conclusions

★ Non-Landau-Ginzburg theory for loss of antiferromagnetic order in a metal
★ New metallic state has “ghost” electron and hole pockets
★ Natural route to $d$-wave pairing with strong pairing at the antinodes and weak pairing at the nodes
★ Paired electron pockets are expected to lead to valence-bond-solid modulations at low temperature
STM studies of the underdoped superconductor

$\text{Ca}_{1.90}\text{Na}_{0.10}\text{CuO}_2\text{Cl}_2$

$\text{Bi}_{2.2}\text{Sr}_{1.8}\text{Ca}_{0.8}\text{Dy}_{0.2}\text{Cu}_2\text{O}_y$

$a_0 = 3.9\text{Å}$

$a_0 = 5.4\text{Å}$
Topograph

$Ca_{1.90}Na_{0.10}CuO_2Cl_2$

$Bi_{2.2}Sr_{1.8}Ca_{0.8}Dy_{0.2}Cu_2O_y$

Intense Tunneling-Asymmetry (TA) variation are highly similar

$dI/dV$ Spectra

![Graphs showing $dI/dV$ spectra for $Ca_{1.90}Na_{0.10}CuO_2Cl_2$ and $Bi_{2.2}Sr_{1.8}Ca_{0.8}Dy_{0.2}Cu_2O_y$.]

$\text{Ca}_{1.90}\text{Na}_{0.10}\text{CuO}_2\text{Cl}_2$

$\text{Bi}_{2.2}\text{Sr}_{1.8}\text{Ca}_{0.8}\text{Dy}_{0.2}\text{Cu}_2\text{O}_y$

Tunneling Asymmetry (TA)-map at $E=150\text{meV}$

$Ca_{1.90}Na_{0.10}CuO_2Cl_2$  

$Bi_{2.2}Sr_{1.8}Ca_{0.8}Dy_{0.2}Cu_2O_y$

Tunneling Asymmetry (TA)-map at $E=150\text{meV}$

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Tunneling Asymmetry (TA)-map at $E=150\text{meV}$

$\text{Ca}_{1.90}\text{Na}_{0.10}\text{Cu}_{2}\text{O}_2\text{Cl}_2$

$\text{Bi}_{2.2}\text{Sr}_{1.8}\text{Ca}_{0.8}\text{Dy}_{0.2}\text{Cu}_{2}\text{O}_y$

Indistinguishable bond-centered TA contrast

with disperse $4a_0$-wide nanodomains

TA Contrast is at oxygen site (Cu-O-Cu bond-centered)

R map (150 mV)

$Ca_{1.88}Na_{0.12}CuO_2Cl_2$, 4 K

TA Contrast is at oxygen site (Cu-O-Cu bond-centered)

Evidence for a predicted valence bond supersolid

Conclusions

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- Paired electron pockets are expected to lead to valence-bond-solid modulations at low temperature
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★ Needed: theory for transition to “large” Fermi surface at higher doping