Thoughts on the Pseudogap

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Outline

1. Impact of pseudogap on spin fluctuation mediated pairing
   Mishra, Chatterjee, Campuzano, Norman, Nature Physics 10, 357 (2014)

2. d-wave charge order from spin fluctuations
Phase Diagram of the Cuprates

What is the Pseudogap Due to?

1. Spin singlets
2. Pre-formed pairs
3. Spin density wave
4. Charge density wave
5. d density wave
6. Orbital currents
7. Flux phase
8. Stripes/nematic
9. Valence bond solid/glass
10. Combination?
\[ A(k, \omega) = I(k, \omega) + I(-k + 2k_F, -\omega) \]  
(spectral function)

\[ \chi_0(q, \Omega) = \int_{-\infty}^{\infty} d\omega' \int_{-\infty}^{\infty} d\omega \frac{f(\omega) - f(\omega')}{\omega - \omega' + \Omega + i0^+} \frac{1}{N} \sum_k A(k + q, \omega)A(k, \omega') \]  
(p-h bubble)

\[ \chi(k, \Omega) = \frac{\chi_0(k, \Omega)}{1 - U\chi_0(k, \Omega)} \]  
(dynamic susceptibility)

\[ V(k, \Omega) = U^2 \left[ \frac{3}{2} \chi(k, \Omega) - \frac{1}{2} \chi_0(k, \Omega) \right] \]  
(pair potential)

\[ \Sigma(k, i\omega_n) = T \sum_{q, \omega_m} V(k - q, i\omega_n - i\omega_m)G_0(q, i\omega_m) \]  
(normal self-energy)

\[ -\frac{T}{N} \sum_{k', \omega_m} V(k - k', i\omega_n - i\omega_m)P_0(k', i\omega_m)\Phi(k', i\omega_m) = \Phi(k, i\omega_n) \]  
(gap equation)

\[ P_0(k', i\omega_m) = G(k', i\omega_m)G(-k', -i\omega_m) \]  
(pairing kernel)
ARPES data from a Bi2212 single crystal ($T_c=90K$, $T=140K$)

Kaminski et al, PRL (2001)
$\chi(q,\omega)$ for $U = 860$ meV (left) and 800 meV (right) using ARPES Greens functions.
d-wave eigenvalue versus temperature using ARPES Greens functions
(FBZ is full Brillouin zone, FSR is Fermi surface restricted)
$$-\frac{T}{N_\phi} \sum_{\phi', \omega_m} V_{nm}^{\phi\phi'} P_0(\phi', i\omega_m) \Phi(\phi', i\omega_m) = \Phi(\phi, i\omega_n)$$

(FS restricted gap equation)

$$V_{nm}^{\phi\phi'} = V(k_{Fx}' - k_{Fx}, k_{Fy}' - k_{Fy}, i\omega_n - i\omega_m).$$

(FS restricted pair interaction)

$$T \sum_{\omega_n} \int_0^{2\pi} \frac{d\phi}{2\pi} \nu \cos^2(2\phi) P_0(\phi, i\omega_n) = 1.$$ 

(weak coupling gap equation)

$$G(k, i\omega_n) = -\frac{i\omega_n + i\Gamma sgn(\omega_n) + \xi_k}{(\omega_n + \Gamma sgn(\omega_n))^2 + \xi_k^2 + \Delta_k^2}.$$ 

(model Greens function)

$$V(k, \Omega) = \frac{3}{2} g_{sf}^2 \frac{\chi Q}{\xi_{AF}^2 + 2 + \cos k_x + \cos k_y - i\Omega/\Omega_{sf}}.$$ 

(MMP pair interaction)
Weak coupling d-wave eigenvalue vs $T$ for various pseudogaps $\Delta_0$ [inset is $T_c$ versus $\Delta_0$ (green curve) and $T_c$ vs $\Gamma$ (black curve)]
$T_c$ vs pseudogap ($\Delta_0$) for various $\Gamma$ using MMP pair interaction (inset) [dashed line is temperature maximum of $\lambda$ vs $\Delta_0$ for $\Gamma=0$]
d-wave eigenvalue $\lambda$ vs $T$ for various $\Delta_0$ (main panel)
CONCLUSION (part 1)

Pair breaking effect of the pseudogap is so strong that $T_c$ should be suppressed to zero UNLESS the pseudogap itself is due to pairing

OR

the transition is driven instead by the $T$ dependence of the interaction

Maier, Staar, Scalapino, arXiv:1507.06206
d-wave superconductivity and d-wave charge order
Two sides of the same coin?

Hayward et al, Science (2014)
The work of Sachdev and others has motivated new experiments designed to look for d-wave charge order by x-rays and STM.
Fourier STM

Fujita et al, PNAS (2014)
Problem 1 – itinerant models tend to predict diagonal (Q,Q) order

Norman, PRB (2007); Melikyan & Norman, PRB (2014)

Sachdev & La Placa, PRL (2013)

Problem 2 – itinerant models typically rely on nesting/hot spots
To address this, we will solve full Brillouin zone strong coupling eqs.

\[
T \sum_{k', \omega_m} V(k - k', i\omega_n - i\omega_m) G(k' - \frac{Q}{2}, i\omega_m) G(k' + \frac{Q}{2}, i\omega_m) \Phi^Q(k', i\omega_m) = \lambda \Phi^Q(k, i\omega_n)
\]

\[
V(k, \Omega) = \frac{3}{2} g_{sf}^2 \frac{\chi_Q}{\xi_{AF}^{-2} + 2 + \cos k_x + \cos k_y + i \frac{\Omega}{\Omega_{sf}}}
\]

\( g_{sf}^2 \chi_Q \) – adjusted to get d-wave superconducting \( T_c \)
\( \Omega_{sf} \) – set by energy scale of spin fluctuations (RIXS, INS)
\( \xi_{AF} \) – set by q dependence of spin fluctuations (INS)

\( G \) – (1) bare G, but based on renormalized dispersion from ARPES
(2) full G dressed by spin fluctuations
Strong coupling calculations using a renormalized bare Greens function do not find bond charge order (left); using a fully dressed $G$ leads to an additional suppression of diagonal charge order as well (right).
Going to longer antiferromagnetic correlation lengths does not really change the story.
Inclusion of a modest coupling to $B_{1g}$ phonons does not help either.
CONCLUSION (part 2)

An itinerant model for the charge order is unlikely

The d-wave order is likely due to Coulomb repulsion between the doped holes on the oxygen sites, with each unit cell maintaining the same hole count

O s-wave

O d-wave