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Possibility of $d + is$ superconductivity in the tJ model: Implications for cuprate high-T_c superconductors

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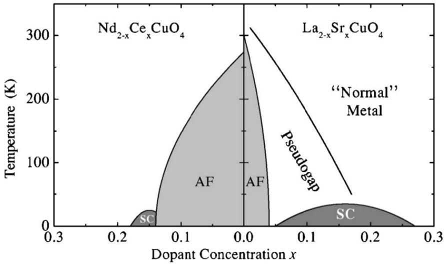
Overview

- Brief review of cuprate phase diagram – what are we after?
- *tJ*-model and *d*-wave superconductivity
- Treatment of fluctuations
- Self-consistent theory

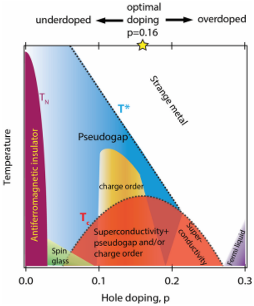
Highlights

- Fluctuations are crucial (no surprise!)
- *d*-SC is *intrinsically unstable* at low doping owing to fluctuations
- $d + is$ state develops at low doping
- Results consistent with many recent experiments

Brief Review



(Damascelli et al. (2003))



(Vishik et al. (2015))

- Phase diagram evolving over last 30 years!
- Underdoped cuprates: *d*-wave state fragile
- Nodeless superconductivity (e. g., Vishik et al. *PNAS* (2012), Razzoli et al., *PRL* (2013))
- Charge density waves/ time reversal breaking (e. g., Karapetyan et al. *PRL* (2014))

Desideratum

- A model that brings out as many of these features

Model and Methods

- t-J Model (Zhang *et al*, 1988)

$$H_{tJ} = -\sum_{\substack{i,m \\ \sigma}} t_m \mathcal{P} c^{\dagger}_{i+m\sigma} c_{i\sigma} \mathcal{P} + J \sum_{\langle i,j \rangle} \left(\mathbf{S}_i \cdot \mathbf{S}_j - \frac{1}{4} n_i n_j \right)$$

projection $\mathcal{P}$ forbids double occupancy

- Low energy physics via Gutzwiller factors

$$H_G = -g_t(p) \sum_{\substack{i,m \\ \sigma}} t_m c^{\dagger}_{i+m\sigma} c_{i\sigma} + g_s(p) J \sum_{\langle i,j \rangle} \mathbf{S}_i \cdot \mathbf{S}_j - g_n(p) J \sum_{\langle i,j \rangle} \frac{1}{4} n_i n_j$$

(Zhang *et al*, 1988; Anderson *et al*, 1988)

- Parameters suitable for cuprates (Fukuyama *et al*, 2008; Baskaran *et al*, 1987)

$t' = -0.3t$ $\quad$ $g_t(p) = p$
$J = 0.3t$ $\quad$ $g_s(p) = g_n(p) = 1$
p – hole doping

Functional Methods for *tJ* Model

- t-J model (H_G) recast

$$H = -g_t(p)\sum_{i,m,\sigma} t_m c^\dagger_{i+m\sigma} c_{i\sigma} - J_P \sum_{\langle i,j\rangle} b^\dagger_{ij} b_{ij}$$
$$- J_K \sum_{\langle i,j\rangle} \chi^\dagger_{ij}\chi_{ij} - \mu_f \sum_{i,\sigma} c^\dagger_{i\sigma\lambda} c_{i\sigma}$$

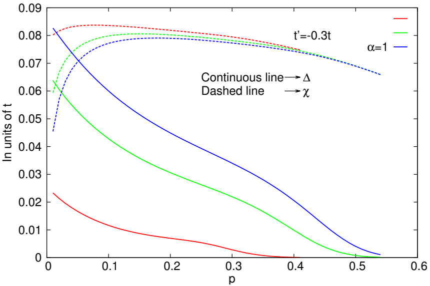
where

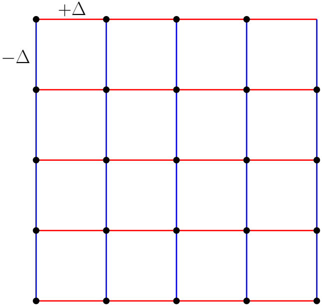
$$b^\dagger_{ij} = (c^\dagger_{i\uparrow} c^\dagger_{j\downarrow} - c^\dagger_{i\downarrow} c^\dagger_{j\uparrow})/\sqrt{2}, \quad \chi^\dagger_{ij} = (c^\dagger_{i\uparrow} c_{j\uparrow} + c^\dagger_{i\downarrow} c_{j\downarrow\lambda})/\sqrt{2}$$
$$J_P = J(g_s + g_n)/2, \quad J_K = J(g_s - g_n)/2$$

- Hubbard-Stratanovich decoupling of J_p and J_K terms
- Saddle point + fluctuations using functional integral techniques

d-SC Saddle Point

- *d*-SC saddle point, Δ – *d*-pairing amplitude





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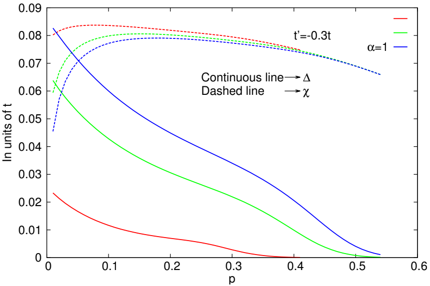
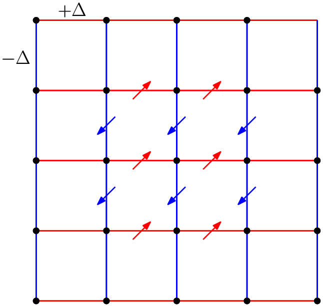
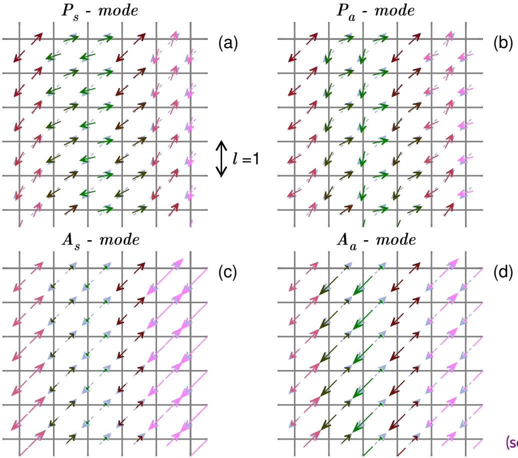




- *d*-pairing can be viewed as “anti-ferromagnetically” ordered planar spins living on the bonds
- What is the fate of the *d*-wave state if fluctuations are included?

Fluctuations of the *d*-SC state

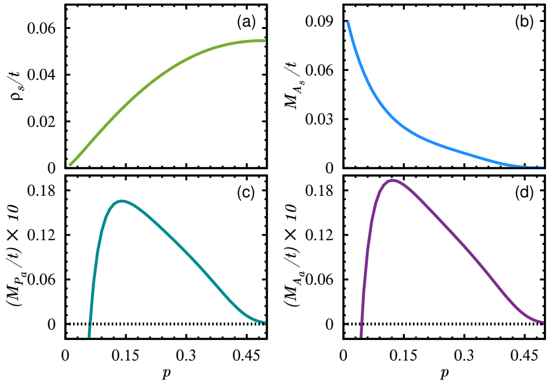
- Pairing amplitude – $\Delta_{ij} = |\Delta_{ij}| e^{i\theta_{ij}}$
- Four types of modes



- P_s – symmetric phase mode (gapless)
- P_a – antisymmetric phase mode (gapped)
- A_s – symmetric amplitude mode (gapped)
- A_a – antisymmetric amplitude mode (gapped)

(see also Kotliar, 1988, Paramekanti et al. 2000)

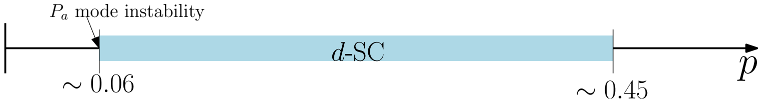
Properties of Collective Fluctuations (Mallik et al. *EPL* (2017))



- ρ_s – superfluid stiffness behaves as expected
- Symmetric amplitude mode ("Higgs") is always massive (gapped)
- Both antisymmetric modes are unstable at low doping – physics owes to strong correlations
- *d*-SC state is intrinsically unstable at low doping!

Physics at Low Doping

- Saddle point ground state: *d*-SC from $p \approx 0.06$ to $p \approx 0.045$



Physics at Low Doping

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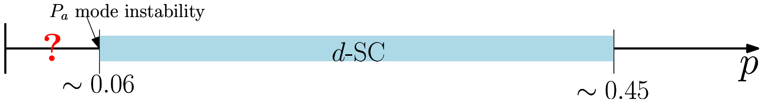
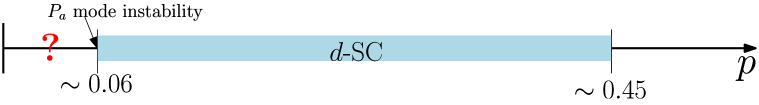


What happens for $p < 0.06$?

Physics at Low Doping

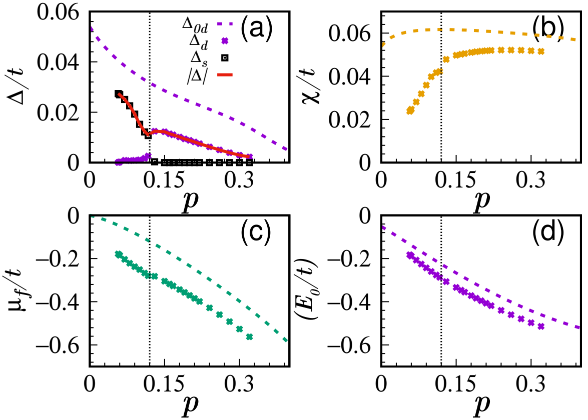
- Saddle point ground state: *d*-SC from $p \approx 0.06$ to $p \approx 0.045$



What happens for $p < 0.06$?

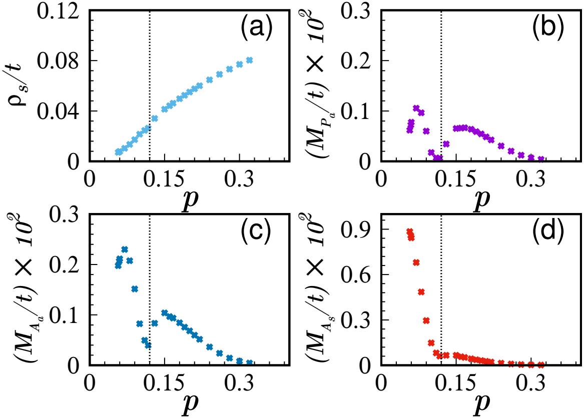
- A *self-consistent* functional calculation performed (see Diener et al. *PRA* (2008), also upcoming paper)
- Self-consistent formulation is implemented numerically
- Saddle point is significantly modified by fluctuations in the self-consistent treatment

Self-Consistent Treatment: Results



- The antisymmetric phase mode instability is pushed to a higher doping of $p = 0.12$...d-SC when $0.12 \lesssim p \lesssim 0.33$
- $d + is$-SC state in the regime $0.06 \lesssim 0.12$ (Kotliar *PRB* (1988), Vojta et al., *PRB* (2000))
- $d + is$-SC state is nodeless!

Self-Consistent Treatment: Results



- Superfluid density ρ_s continues to have the well known linear behavior with doping $\rho_s \sim p$ (Uemura et al. *PRL* (1989))
- Transition from d-SC to $d + is$-SC is via the closing of the P_α mode gap (and reopening on the $d + is$ side)

Implications for Cuprate Physics

- Ground state phase diagram of the *tJ* model from the self-consistent scheme

- Doping range of *d*-SC consistent with experiment (vast improvement over simple saddle point)
- Predictions of Δ etc. are consistent with ARPES(Vishik et al. *PNAS* (2012)) and STM(Lawler et al. *Nature* (2010), He et al., *Science* (2014)) experiments
- Several experiments(Vishik et al. *PNAS* (2012),, Razzoli et al. *PRL*(2013)) note changes occurring in the doping regime of $p \approx 0.1$: transition from *d*-SC to $d + is$-SC is a strong candidate (particularly for nodeless superconductivity)
- ρ_s is consistent with well established behavior even in $d + is$ state at low doping
- $d + is$ by itself cannot explain Kerr rotation experiments – however, $d + is$ in conjunction with a charge density wave can give raise to a Kerr signal!

Summary

What is done

- A detailed analysis of the *tJ* model in a self-consistent functional framework

Key results

- Fragility of *d*-SC state at underdoping from *its own* fluctuations
- Ground state has $d + is$-SC at low doping and *d*-SC at higher doping

- Offers a simple framework to understand many of the recent experiments while remaining consistent with well established results

Coming soon to the arXiv

...also related talk K30.00003, Wednesday, 8:24AM