Inhomogeneous spin and charge densities in d-wave superconductors

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Cooperative Phenomena in Solids: Metal-Insulator-Transitions and Ordering of Microscopic Degrees of Freedom
Outline

- Resonances in d-wave superconductors
- Impurities & field-induced antiferromagnetism
  - common origin
- Coexistence of superconductivity and charge order
- Stripe patterns and finite momentum pairing
Collaborators

**d-wave superconductivity and antiferromagnetism**

- Markus Schmid, University of Augsburg
- Peter Hirschfeld, University of Florida, Gainesville
- Brian Andersen, Niels Bohr Institute, Copenhagen

**d-wave superconductivity and charge order**

- Florian Loder, University of Augsburg
- Thilo Kopp, University of Augsburg
Insights & Puzzles from STM Spectra of Cuprate Superconductors

- sharp conductance peaks near Zn impurities close to zero bias
- gap inhomogeneities and negative coherence peak height to gap value correlation
- split bound states in d-wave vortex cores
- 4-unit cell checkerboard charge density modulations

J.C. Davis (Cornell), A. Yazdani (Princeton), Kapitulnik (Stanford)

Theory issues:

- $\tau_1$ versus $\tau_3$ impurities
- spatial LDOS structure
- quasiparticle interference patterns
- nucleation of spin and charge order

P. Hirschfeld, C.S. Ting, A. Balatsky, T. Devereaux, P. Lee, …
Imaging Zn impurity atoms on BSCCO

Gap Inhomogeneity in BSCCO

A. C. Fang et al., PRL 96, 017007 (2006)
Local density of states in the vortex core of YBCO

- I. Maggio-Aprile et al., PRL 75, 2754 (1995)
STM spectra of the vortex core in BSCCO

S. H. Pan et al., PRL 85, 15367 (2000)
Signatures for the coexistence of antiferromagnetism and superconductivity

- $\mu$-on spin rotation in underdoped YBCO and in LSCO  
  Miller et al. 2006  
  Panagopoulos et al. 2002

- Evidence for antiferromagnetic vortex cores in Tl$_2$Ba$_2$CuO$_6$ from NMR relaxation rate  
  Kakuyanagi et al. 2003

- Elastic neutron scattering with $(\pi - \delta, \pi)$ incommensurate antiferromagnetism in superconducting LSCO  
  Wakimoto et al. 2001

- Zn impurities induced inhomogeneous antiferromagnetic order in optimally doped LSCO  
  Kimura et al. 2003

- Field-induced antiferromagnetism in superconducting underdoped LSCO from neutron diffraction  
  Lake et al. 2002
Field-induced antiferromagnetic order in underdoped LSCO

Focus issues

- Impurity versus field-induced antiferromagnetism
- Role of impurity resonances & vortex bound states for the nucleation of antiferromagnetism
- Temperature dependence of the staggered magnetization
Model and Calculational Tools

- Pairing Hamiltonian in an external magnetic field:

\[
H = \sum_{\langle ij \rangle \sigma} t_{ij} \exp \left[ i \frac{\pi}{\phi_0} \int_i^j \mathbf{A} \cdot d\mathbf{l} \right] \hat{c}_{i\sigma}^\dagger \hat{c}_{j\sigma} + \sum_{\langle ij \rangle} \left( \Delta_{ij} \hat{c}_{i\uparrow}^\dagger \hat{c}_{j\downarrow} + H.c. \right) 
+ \sum_{i\sigma} \left( U_{n_i,-\sigma} + V_i^{imp} - \mu \right) \hat{c}_{i\sigma}^\dagger \hat{c}_{i\sigma}
\]

- d-wave pairing potential: \( \Delta_{ij} = -V_d \langle \hat{c}_{i\downarrow} \hat{c}_{j\uparrow} \rangle \)

- self-consistent Bogoliubov-de Gennes (BdG) equations

\[
\sum_j \begin{bmatrix} H_{ij,\sigma} & \Delta_{ij} \\ \Delta_{ij}^* & -H_{ij,-\sigma}^* \end{bmatrix} \begin{bmatrix} u_{jn} \\ v_{jn} \end{bmatrix} = E_n \begin{bmatrix} u_{in} \\ v_{in} \end{bmatrix}
\]

- supercell method & magnetic Bloch theorem
Impurity-Induced Antiferromagnetism

Charge Density  

Order Parameter  

Magnetization

- LDOS (next to impurity)
- \( U > U_c \): impurity induces short-range AF order
- Origin: spin splitting of the (near) zero-energy resonance
Field-induced Antiferromagnetism

Charge Density

Order Parameter

Magnetization

doping = 10%, $V_{imp} = 0$, $\Phi = 2\Phi_0$

- $U = 2.2t$ (magnetized)
- $U = 0$ (unmagnetized)

- vortex core LDOS
- AF vortex core for $U > U_c$
- Origin: spin splitting of the vortex bound state
Field-Induced Antiferromagnetism – T Dependence

Structure Factor

LDOS at the vortex center

doping 10%, B = 59.2 Tesla, \( V_{\text{imp}} = 0 \)

|\(|M(q)|^2| \) (integrated)

Temperature \([t]\)

\[0\] 0.05 0.1 0.15 \(T_c\)

\[U=2.5t\] \[U=2.6t\] \[U=2.7t\] \[U=2.8t\] \[U=2.9t\]

doping = 10%, \( V_{\text{imp}} = 0 \), \( \Phi = 2\Phi_0 \)

LDOS

Energy \([t]\)

\[0\] \(-1\) 0 1

- \(|M(q)|^2(T)\) negative curvature, 'order parameter like'
- no domain walls
- simultaneous onset of bound-state splitting & magnetization
Two Strong Non-magnetic Impurities

Charge density

Magnetization

Structure factor

doping = 10%, $V_{\text{imp}} = 10t$, $B = 0$

- negative curvature of $|M(q)|^2(T')$
- $T$ dependence as for field induced antiferromagnetism
- possible reason: absence of domain walls
Out-of-plane Sr atoms act as weak potential scatterers on the in-plane electrons.

\[ \text{La}_{2-x}\text{Sr}_x\text{CuO}_4 \]

impurity concentration = doping
Combined Disorder & Field-Induced Antiferromagnetism

Charge Density | Order Parameter | Magnetization

$\Phi = 0$

$\Phi = 2\Phi_0$
Structure Factor for Different Impurity Configurations

\[ \Phi = 0 \]

\[ \Phi = 2\Phi_0 \]
Averaged Structure Factor

\[ \Phi = 0 \]

\[ \Phi = 2\Phi_0 \]

Lake’s experiment

- incommensurate AF order
  \[ \mathbf{Q} = (\pi \pm \delta, \pi) \]
zero-field signal rises linearly upon cooling

field-induced signal increases 'order parameter like'

origin for different curvatures: antiphase domain walls
More results and details on the poster:

- Impurity and field-induced antiferromagnetism in cuprate superconductors

- by Markus Schmid, Brian Andersen, Peter Hirschfeld, and A.P.K.