Competing Phases in Cuprate Superconductors

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W. A. Atkinson, Phys. Rev. B **71** 024516 (2005)

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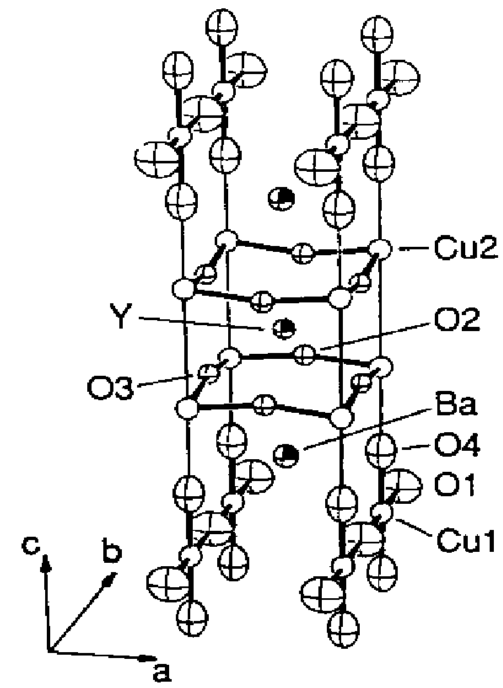
Overview

- Introduction to High T_c Superconductors; Evidence for Coexisting Order.
- The calculations; self-consistent solutions.
- Excitation spectrum.

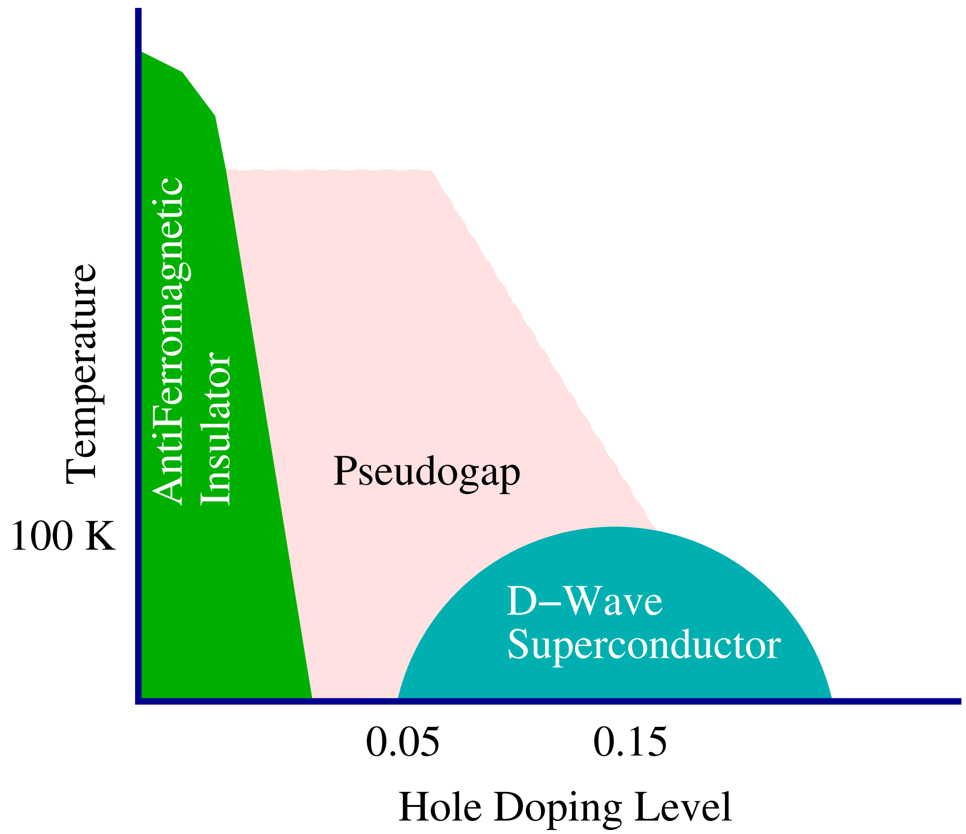
Crystal Structure

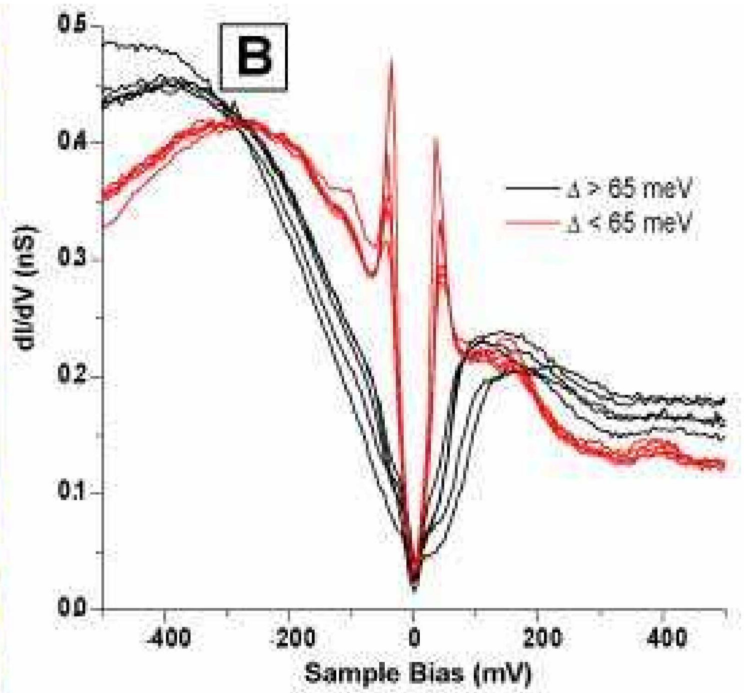
- Electrons move within 2D Cu-O planes.
- Weak c-axis conductivity.
- Tune properties by chemical doping (O1 sites or Ca/Y substitution).



Narrow Bands & Low Dimensions $\Rightarrow$ Strong Correlations

Generic Phase Diagram





McElroy et al., cond-mat/0406491

Evidence for Phases Coexisting with Superconductivity

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Stripes (spin-charge separation). particularly in La-based cuprates, but also $YBa_2Cu_3O_{7-\delta}$.	Tranquada et al., Nature **375**, 561 (1995); Mook et al., Nature **395**, 580 (1998).
Glassy magnetic phases (particularly in $YBa_2Cu_3O_{7-\delta}$)	Buyers et al. in $YBCO_{6.35}$; BSCCO: Panagopoulos et al., Solid State Commun. **126**, 47 (2003).
Weak charge modulations in $Bi_2Sr_2CaCu_2O_8$	McElroy et al., cond-mat/0406491; Howald et al., PRB **67** 014533 (2003).

Approach: take a simple model of competing AF and SC phases and study excitation spectrum.

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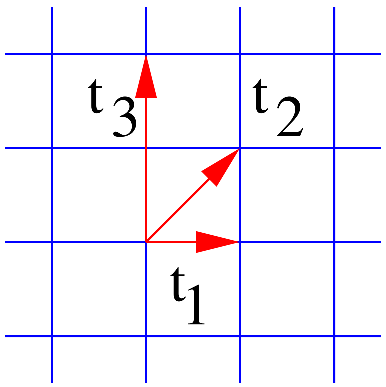
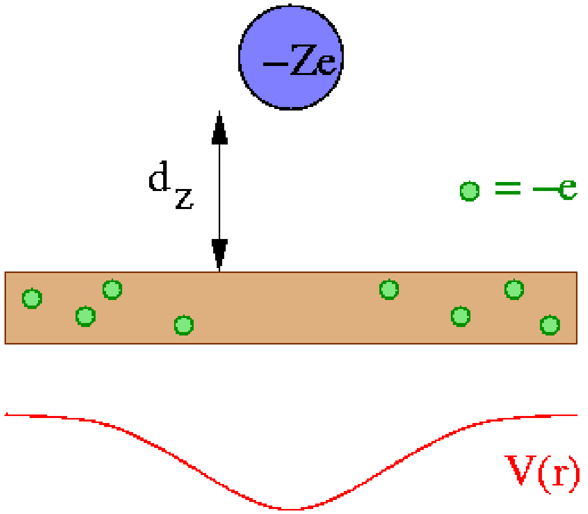
Mean-field Model

$$H = H_0 + H_{\text{int}}$$



$$t_1 = -1 \quad t_2 = 0.25 \quad t_3 = 0.1$$



$$H_0 = \sum_{i,j,\sigma} t_{ij} c^\dagger_{i\sigma} c_{j\sigma} \underbrace{- Z \sum_{i,\mathbf{R}} V(\mathbf{r}_i - \mathbf{R}) \hat{n}_i}_{\text{Coulomb potential due to donors}}$$

$$H_{\rm int} = \underbrace{\sum_i U \hat{n}_{i\uparrow}\hat{n}_{i\downarrow}}_{\text{Hubbard}} + \underbrace{\frac{1}{2}\sum_{i\neq j} V(\mathbf{r}_i - \mathbf{r}_j)\hat{n}_i\hat{n}_j}_{\text{Long range Coulomb}} + \underbrace{\frac{J}{2}\sum_{\langle ij\rangle} \hat{\mathbf{S}}_i \cdot \hat{\mathbf{S}}_j}_{\text{N.N. Exchange}}$$

$$n_{i\sigma} = \langle c^\dagger_{i\sigma} c_{i\sigma}\rangle \quad \Delta_{ij} = -\frac{3J}{4}\langle c_{j\downarrow}c_{i\uparrow} + c_{j\uparrow}c_{i\downarrow}\rangle$$

$$m_z(\mathbf{r}_i) = \tfrac{1}{2} e^{i\mathbf{Q}\cdot\mathbf{r}_i}(n_{i\uparrow} - n_{i\downarrow})$$
$$h(\mathbf{r}_i) = 1 - (n_{i\uparrow} + n_{i\downarrow})$$

Comments about mean-field calculations

- In the neighbourhood of a negatively charged impurity, the local hole concentration is high. AF moments form preferentially in underdoped regions. Local electronic spectrum is controlled by local potential. $\Rightarrow$ Other mechanisms possible. (eg. variations of effective mass)

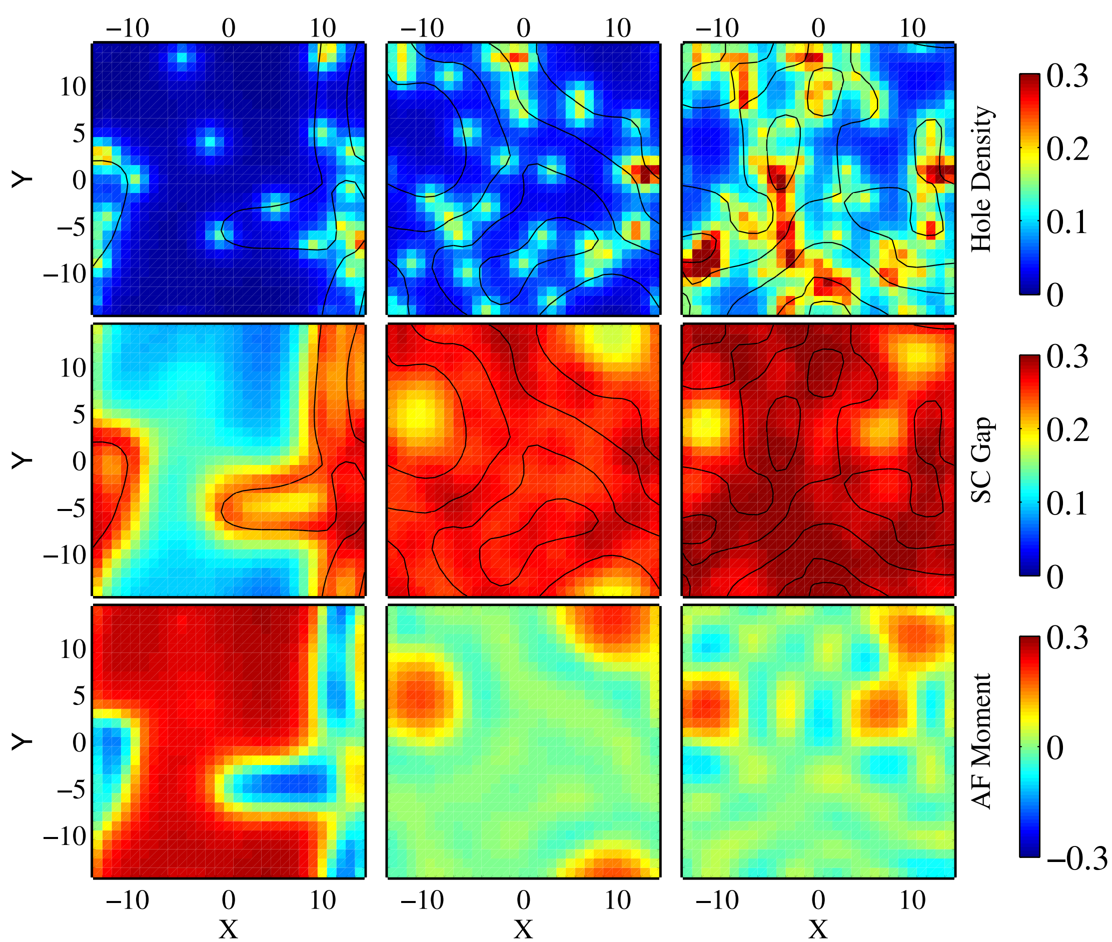
- RVB $\Rightarrow J \sim (1-n/2)^{-2}$. Calculations ignore variations of J (and therefore Δ) with doping.

- Missing dynamics (spin-waves, other collective modes) $\Rightarrow$ tends to overestimate m_z.

- Calculations find local minimum of energy. Looking for glassy solutions.

- Useful for studying large/disordered systems.

Self-Consistent Solutions



- SC order is suppressed by AF. Phases compete.
- AF phase is metallic (SDW $\equiv$ AF here).
- Correlation length $\xi_{AF} \sim t/Um_z$.
- Substantial moment forms if distance d between domain walls is $d > \xi_{AF}$. However, moment is finite everywhere.
- AF moment is suppressed with doping by a proliferation of domain walls.

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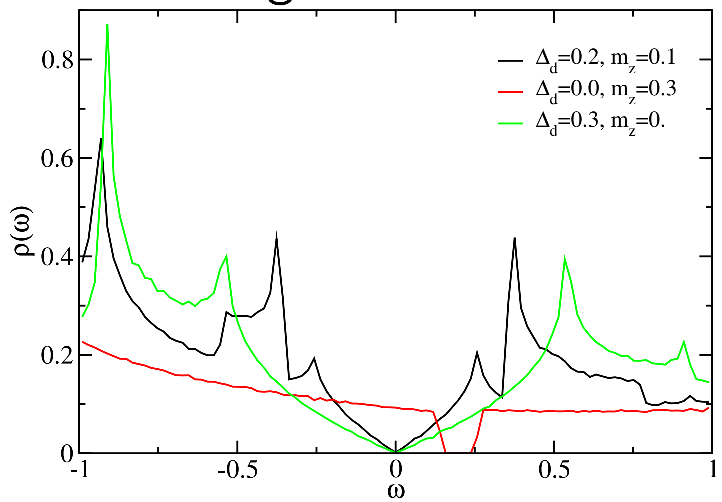
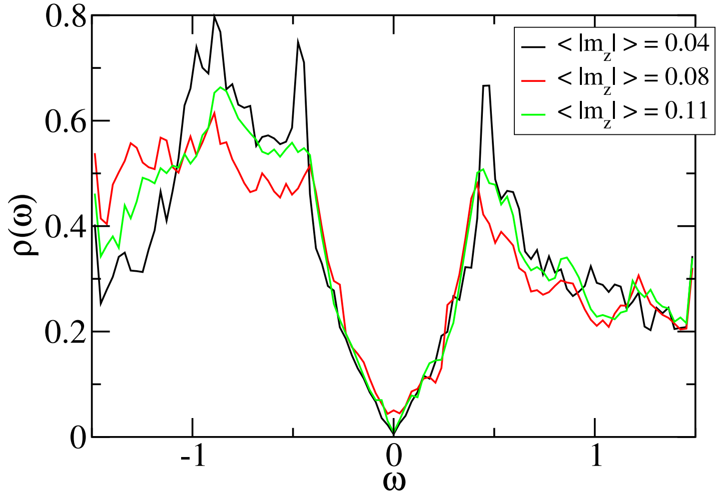
Density of States

Homogeneous Order



Inhomogeneous Order

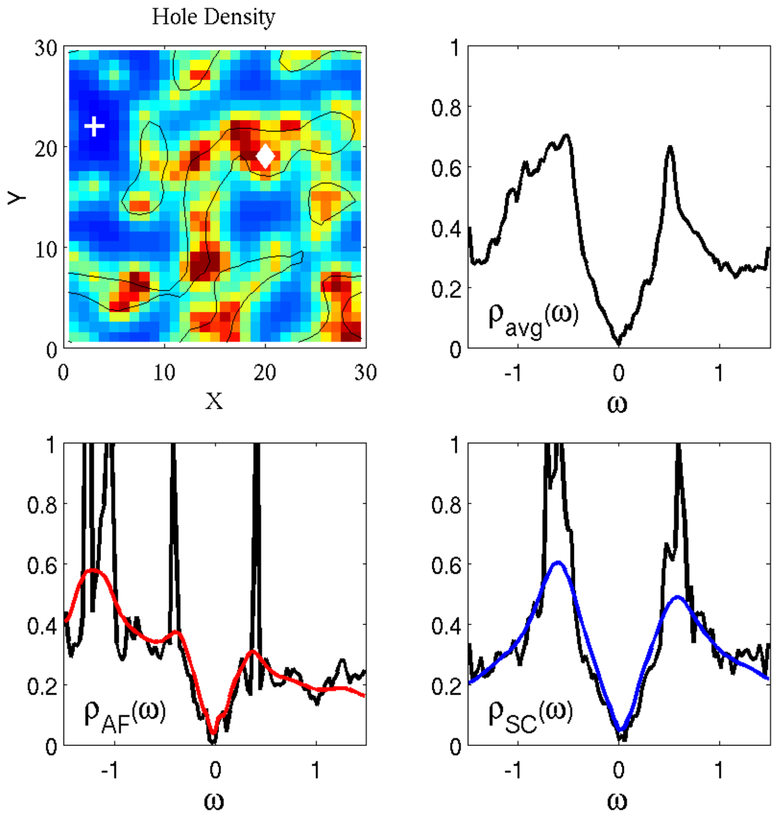


$$\mathbf{H}_\mathbf{k} = \begin{bmatrix} \epsilon_\mathbf{k} & \Delta_\mathbf{k} & -M & 0 \\ \Delta_\mathbf{k} & -\epsilon_\mathbf{k} & 0 & -M \\ -M & 0 & \epsilon_{\mathbf{k}+\mathbf{Q}} & \Delta_{\mathbf{k}+\mathbf{Q}} \\ 0 & -M & \Delta_{\mathbf{k}+\mathbf{Q}} & -\epsilon_{\mathbf{k}+\mathbf{Q}} \end{bmatrix}$$

$$M = U m_z$$

- Low energy DOS largely unaffected.
- Coherence peaks suppressed. Spectral weight shifted on energy scale M.

Local Density of States



- Characteristic LDOS for different regions.
- Cohrence peak weight is reduced in AF regions (wiped out by inelastic scattering).

$$\rho(\mathbf{r}_i,\omega) = \sum_{n,\sigma} \frac{|\Psi_{n,\sigma}(\mathbf{r}_i)|^2}{\omega - E_n - \Sigma(\omega)}$$

$$\Sigma(\omega) = \Gamma\omega^3/(\omega^3+\Delta^3)$$

Conclusion

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- Low T tunneling spectrum consistent with coexisting order provided m_z is not too big.

- Doping dependence of $\lambda^{-2}(T)$ consistent with increasing m_z as one underdopes.