Role of Interlayer Coupling on the Competition Between Charge Order and Superconductivity

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APS March Meeting
Mar. 6, 2018
Outline

• Light induced enhancement of pairing correlations - *Context*

• Competing charge order and superconductivity in cuprates - *A quick survey*

• Competition of orders in a bilayer - *Model and phase diagram*

• Effects of phase pinning - *The role of charge order domains*
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• Effects of phase pinning - *The role of charge order domains*
Nonlinear lattice dynamics as a basis for enhanced superconductivity in YBa$_2$Cu$_3$O$_{6.5}$

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ABSTRACT

Recent advances in laser technology have made it possible to generate shaped pulses at terahertz frequencies. These pulses are especially useful to selectively drive collective modes of solids, for example, to drive materials in a fashion similar to what done in the synthetic environment of optical lattices. One of the most interesting applications involves the creation of non-equilibrium phases with new emergent properties. Here, I discuss how coherent control of the lattice to favour superconductivity at ultra-high temperatures, sometimes far above the thermodynamic critical temperature, 123a.

ARTICLE HISTORY

Received 21 September 2017
Accepted 13 November 2017

KEYWORDS

Superconductivity; ultrafast science; nonlinear phononics; structural dynamics

Optically induced Stripe-Ordered Superconductivity

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One of the most intriguing features of some high-temperature superconductors is an interplay between one-dimensional "striped" spin order and superconductivity. We used mid-infrared femtosecond pulses to transform one of the nonsuperconducting La$_2$.675Eu$_0$.25Y$_{1.25}$Cu$_3$O$_6$ into a transient stripe-ordered superconductor. The emergence of coherent interlayer transport was evidence for Josephson plasma resonance in the c-axis optical properties, which needed to form the superconducting phase is estimated to be 1 to 2 picoseconds, which is significantly faster than expected. This places stringent new constraints on our understanding of striped order and its relation to superconductivity.

Optically induced Superconductivity

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(Received 18 March 2014; revised manuscript received 25 August 2014; accepted 13 November 2014)
Motivation: Light Induced Superconductivity in cuprates

• Mid-infrared optical excitation resonant with c-axis phonons.

• This leads to displacement of the apical oxygens.

Features in the optical conductivity

\[ \sigma(\omega) = \sigma_1(\omega) + i\sigma_2(\omega) \]


W. Hu et al., Nat. Mater. 13, 705 (2014)
Effects of periodic modulation

Driving the system alters the structure of the system leading to

- Quasi-static shift of plane separation

- Oscillation induced enhancement of $t_z$

Generically function to enhance the interlayer coupling
How can this enhance superconductivity?
Competition of superconductivity and charge order

- Charge order is experimentally seen to compete with superconductivity in these systems.
- A melting of charge order is observed coinciding with emergence of the transient pairing signal.


A model of Copper Oxide planes

The Hamiltonian consists of hopping on square lattice, nearest neighbor exchange, and nearest neighbor Coulomb repulsion.

\[
H = \sum_{i,j} t_{ij} c^\dagger_{i\sigma} c_{j\sigma} + \frac{1}{2} \sum_{\langle i,j \rangle} J \hat{S}_i \cdot \hat{S}_j + \frac{1}{2} \sum_{\langle i,j \rangle} V \hat{n}_i \hat{n}_j
\]

hopping on square lattice, nearest neighbor exchange, and nearest neighbor Coulomb repulsion.

e.g. M.A. Metlitski and S. Sachdev, Phys. Rev. B 82, 075128 (2010)
Mean-field theory of competing orders

\[ \phi(\mathbf{Q}) = \frac{g\phi}{2} \sum_{\mathbf{k},\sigma} f(k) \left\langle c_{\mathbf{k}-\mathbf{Q}/2,\sigma}^{\dagger} c_{\mathbf{k}+\mathbf{Q}/2,\sigma} \right\rangle \]

\[ \Delta = \frac{g\Delta}{4} \sum_{\mathbf{k},\sigma,\sigma'} f(k) \left\langle c_{-\mathbf{k},\sigma}(-i\sigma^2_{\sigma\sigma'}) c_{\mathbf{k},\sigma'} \right\rangle \]

- d-wave superconductivity \( \Delta \)
- d-form-factor density wave (dFF-DW) \( \phi \)
Landau theory of competing orders

\[ F = \alpha_\Delta \Delta^2 + \beta_\Delta \Delta^4 + \alpha_\phi \phi^2 + \beta_\phi \phi^4 + \gamma \phi^2 \Delta^2 \]

\((\phi, \Delta) \in (0, 0), (\phi_0, 0), (0, \Delta_0), (\phi_{co}, \Delta_{co})\)

Mechanism: The role of curvature

- Light Pulse
- Interlayer Coupling
- Charge order
- SC
Mechanism: The role of curvature
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Light Pulse

Interlayer Coupling ↑

Charge order ↓

SC ↑
Including the effect of interlayer coupling

Extend to 3 dimensions and consider the effect of interlayer coupling

When increasing $t_z$:

- $Q_z = 0$ DW is melted
- SC is enhanced

Just increasing $t_z$ is not enough

- Nesting is destroyed at $Q_z = 0$
- **But**, nesting can be preserved for ordering with $Q_z = \pi$
- This effectively decouples the layers as far as the density wave is concerned
Promote phase and orientation to random variables $\phi \rightarrow \phi[O, \theta]$

- $\theta$ - the phase difference of the orders
- $O$ - the relative orientation of the ordering vectors ($\parallel, \perp$)
Averaging over orientation and phase

- \( \theta \) - the phase difference of the orders
- \( O \) - the relative orientation of the ordering vectors

\[
\langle F \rangle_{\theta O} \rightarrow \alpha_\Delta \Delta^2 + \beta_\Delta \Delta^4 + \alpha_\phi \phi^2 + \beta_\phi \phi^4 + \gamma \phi^2 \Delta^2
\]
After averaging

\[
\phi \text{ (meV)} \quad t_z \text{ (meV)}
\]

\[
\Delta \text{ (meV)}
\]
Effect is generic

\[ \sigma_\theta = 1 \quad \text{and} \quad \sigma_\theta = 0.5 \]
Summary

- The perturbation increases effective inter-plane coupling, $t_z$.
- The presence of phase pinning allows increasing $t_z$ to melt charge order.
- Melting of charge order enhances superconductivity.