Superconductivity near CDW instability

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This talk is about superconductivity mediated by collective electron degrees of freedom – the area where Gil is the major player.

Quantum criticality and SC from magnetically-mediated interaction between itinerant electrons.

QC and SC from the interaction between itinerant electrons, mediated by charge fluctuations.

Metamagnetic Quantum Criticality in Metals

CDW order in the cuprates

- Short-range static order, centered around doping $x=1/8$
- Momentum $(0,Q)$ or $(Q,0)$
- Connects end points of Fermi arcs

Comin et al
Da Silva Neto et al
Is charge order = the pseudogap phase?

O. Cyr-Chiniere et al, 2014

Shekhter et al, 2013

Partially ordered CDW is consistent with the observations of discrete orders at temperatures between $T^*$ and $T_{cdw}$.
Charge order with \((Q,0)/(0,Q)\) and discrete symmetry breaking

- CDW order can choose between \((Q,0)\) or \((0,Q)\) \([\text{nematic order}]\)
- It can also differentiate between \(k_0\) and \(-k_0\) \([\text{T-rev. breaking}]\)

\[
\Delta_{Q,k_0}^0 = \sum_{k \approx k_0} <c_{k+Q/2}^+ c_{k-Q/2}> = |\Delta_{Q,k_0}^0| e^{i\psi_{k_0}}
\]

GL analysis:

\[
|\Delta_{Q,k_0}^0| = |\Delta_{Q,-k_0}^0| \quad \cos(2(\psi_{k_0} - \psi_{-k_0})) = \pm 1
\]

If \(\psi_k - \psi_{-k} = \pi/2\) or \(-\pi/2\), time-reversal symmetry is broken

In both cases, discrete symmetry gets broken at a higher \(T\) than \(T_{\text{cdw}}\), at which a true CDW order sets in.
How to obtain CDW?

dependence of CDW order on center of mass momentum $k_0$: it is d-wave with some admixture of s-wave

$$\Delta^Q_{k_0} = \sum_{k \approx k_0} <c^+_{k+Q/2} c_{k-Q/2}>$$

Under $k_0 \rightarrow k_0 + (\pi, \pi)$

$$\text{sgn}[\Delta^Q_{k_0}] = -\text{sgn}[\Delta^Q_{k_0+(\pi, \pi)}]$$

magnitudes are close, but not identical

Expected if CDW is due to repulsive interaction at momentum transfer near $(\pi, \pi)$: a spin fluctuation is a candidate
Spin-fluctuation scenario

Metlitski and Sachdev,
Efetov, Pepin and Meier : (Q,Q) order
La Placa and Sachdev: a generic CDW
Wang & A.C  (Q,0)/(0,Q) order

CDW order in some finite doping range away from SDW
QC/SC near a QCP

NFL + Spin-fluctuation-mediated superconductivity

NFL + Charge-fluctuation-mediated superconductivity

?
I. Charge-fermion model

- fermions + near-critical charge fluctuations
- static interaction between fermions is taken as input

\[ U_{\text{eff}}(q) = g_c^2 \chi_c(q) = \frac{g_c}{\xi_c^{-2} + (q - Q)^2} \]

NFL at CDW QCP, but only at hot spots \((\Sigma(\omega) \sim \omega^{1/2})\)
Pairing: Eliashberg-type theory

Competition between strong dynamical pairing interaction and strong pair-breaking effect from fermionic self-energy

At CDW QCP,

- the overall energy scale is the interaction,
- the dimensionless pairing coupling is of order one

\[ T_c^{\text{ch}} = 0.003 \bar{g}_c \]

Full gap in each “antinodal” region, s-wave and d-wave are degenerate

Castellani, Di Castro, Grilli…..
$T_{c}^{\text{ch}} = 0.003 \overline{g}_c f \left( \frac{\overline{g}_c}{V_F \xi^{-1}_c} \right)$

Looks great, but we don’t know the coupling
Spin-fluctuation-mediated d-wave superconductivity

Charge-fluctuation-mediated superconductivity

The two SC temperatures are comparable if the couplings are comparable.
II. Relation between charge and spin couplings

A way to relate spin and charge couplings is to go back to microscopic model for CDW order due to spin fluctuations and do RPA in the charge channel using for the “bare” interaction the one obtained out of spin fluctuations.

\[ \overline{g}_c \sim \overline{g}_s \quad (\overline{g}_c \approx 2 \overline{g}_s \text{ in RPA}), \]

\[ T_c^{\text{ch}} \text{ is comparable to } T_c^{\text{sp}} \]

Spicy stuff: at a first glance, \( \overline{g}_c \sim \frac{\overline{g}_s^2}{\Lambda} \ll \overline{g}_s \),

In reality, \( \overline{g}_c \sim \frac{g_s^2}{\gamma} \), where \( \gamma \) is Landau damping for spins, \( \gamma \) by itself scales with spin-fermion coupling \( \overline{g}_s \).
Superconductivity near a QCP

Charge-fluctuation-mediated superconductivity

Spin-fluctuation-mediated d-wave superconductivity
Maximum of superconducting Tc at apparent CDW QCP

B. Ramshaw et al (LANL + Cavendish + UBC), Science (2015)
III. In a magnetic field

We analyzed charge-mediated SC

- At QCP, a large field (of order of coupling) is needed to destroy charge-mediated SC
- Away from QCP, a progressively smaller field destroys SC

Charge-mediated SC gets progressively confined to the vicinity of SDW QCP
Experiment: in a field, SC gets progressively confined to QCP

G. Grissonnanche et al, 2014
Conclusions

Superconductivity mediated by near-critical charge fluctuations well may compete with the one mediated by spin fluctuations, even if charge fluctuations are by themselves made out of spin fluctuations
Dear Gil:

and the very best wishes
THANK YOU