Strongly Correlated Superconductivity

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St-John’s, 16 June 2011
The race for absolute zero temperature
On the way towards the target $T=0$

- What happens to electrical resistance?

8 April 1911
Inching our way to room temperature
Attraction mechanism in the metallic state
#1 Cooper pair, #2 Phase coherence

\[
E_P = \sum_{p,p'} U_{p-p'} \psi_{p,p',-p,-p'} \psi_{p,p',-p,-p'}^* \\
E_P = \sum_{p,p'} U_{p-p'} \left( \langle \psi_{p,-p} \rangle \psi_{p',-p, -p'}^* + \psi_{p,-p}^* \langle \psi_{p',-p} \rangle \right) \\
|BCS(\theta)\rangle = \ldots + e^{iN\theta} |N\rangle + e^{i(N+2)\theta} |N+2\rangle + \ldots
Superconductivity everywhere
Superconductivity everywhere

![Pressure-Temperature Phase Diagram](image1)

![Neutron Star](image2)

![Fundamental Particles Chart](image3)
Inching our way to room temperature
High-temperature superconductors
What is special

- TM (not Cu, Au, Fe)
- Cubic
- Stay away from
  - O
  - Magnets
  - Insulators
- Cu
- Layered
- Stay close to
  - O
  - Magnets
  - Insulators
Superconductivity
in the presence of repulsion
Phase diagram

Armitage, Fournier, Greene, RMP (2009)
Layered organic conductors (κ–BEDT-X family)
Phase diagram \((X = \text{Cu}[\text{N(CN)}_2]\text{Cl})\)

S. Lefebvre et al. PRL 85, 5420 (2000), P. Limelette, et al.
Heavy fermions CeMnI$_5$

Figure 1. The structure of the CeMIn$_5$ materials. The Ce (Wykyoff position 1a) atoms are yellow, the In(1) (1c) atoms are orange, the In(2) (4i) are green, and the M atoms are blue (1b). Details of the structural parameters can be found in [10]. Hyperfine interactions in the heavy fermion CeMIn$_5$ systems N J Curro
$115 \text{ (in 2000)}$

Pnictides (2008)

http://www.stanford.edu/~tpd/research_hightc.html
Pnictides

http://physics.aps.org/articles/v3/41
Antiferromagnetism means repulsion
Hubbard model

1931-1980

$$H = - \sum_{<ij>\sigma} t_{i,j} \left( c_{i\sigma}^{\dagger} c_{j\sigma} + c_{j\sigma}^{\dagger} c_{i\sigma} \right) + U \sum_i n_{i\uparrow} n_{i\downarrow}$$

Weak coupling

Strong coupling
Antiferromagnetism and repulsion

Effective model, Heisenberg: $J = 4t^2 / U$
Superconductivity with repulsion

\[ E_P = \sum_{p,p'} U_{p-p'} \psi_{p\uparrow,-p\downarrow} \psi_{p'\uparrow,-p'\downarrow}^* \]
Weak to intermediate coupling

Armitage, Fournier, Greene, RMP (2009)

FLEX, Bickers, Scalapino
Two-particle self-consistent approach, Vilk, Kyung,A.-M.S.T.
• Renormalization group
Strong correlations
Insulator even if $n=1$
Experimental phase diagram BEDT-X

Phase diagram \((X=\text{Cu}[\text{N(CN)}_2]\text{Cl})\)
S. Lefebvre et al. PRL 85, 5420 (2000), P. Limelette, et

CIAR The Canadian Institute for Advanced Research

Bourbonnais Jerome
A quantum traffic jam (A.P.): Mott insulator
Spectral weight transfer

Meinders et al. PRB 48, 3916 (1993)
Cuprates as doped Mott insulators
Experiment: X-Ray absorption

Chen et al. PRL 66, 104 (1991)

Peets et al. PRL 103, (2009), Phillips, Jarrell arXiv

Number of low energy states above $\omega = 0$ scales as $2x +$
Not as $1+x$ as in Fermi liquid

Meinders et al. PRB 48, 3916 (1993)
Theoretical method
Mott transition and Dynamical Mean-Field Theory. The beginnings in $d = \infty$

- Compute scattering rate (self-energy) of impurity problem.
- Use that self-energy ($\omega$ dependent) for lattice.
- Project lattice on single-site and adjust bath so that single-site DOS obtained both ways be equal.

W. Metzner and D. Vollhardt, PRL (1989)
A. Georges and G. Kotliar, PRB (1992)
M. Jarrell PRB (1992)

DMFT, $(d = 3)$
2d Hubbard: Quantum cluster method

Hettler …Jarrell…Krishnamurty PRB 58 (1998)
Kotliar et al. PRL 87 (2001)
Maier, Jarrell et al., Rev. Mod. Phys. 77, 1027 (2005)
Solving cluster in a bath problem

- Continuous-time Quantum Monte Carlo calculations to sum all diagrams generated from expansion in powers of hybridization.


The « normal » state
Normal state phase diagram
Mott felt away from $n = 1$

Giovanni Sordi

Kristjan Haule


- first order transition at finite doping between two metals
- it is associated to Mott physics: all signatures of the first order transition can be traced back to Mott critical point

⇒ signature of the Mott transition in the 2D Hubbard model extends way beyond half filling!
criticality originates from
first order transition at finite doping
coming from influence of Mott physics well beyond half filling!

G. Sordi, K. Haule, A.-M.S.T PRL, 104, 226402 (2010)
and arXiv:1102.0463
Strongly Correlated Superconductivity

Phase diagram
Exact diagonalization as impurity solver ($T=0$).
CDMFT global phase diagram

Kancharla, Kyung, Civelli, Sénéchal, Kotliar AMST
Consistent with following experiment

H. Mukuda, Y. Yamaguchi, S. Shimizu, … A. Iyo JPSJ 77, 124706 (2008)
Experimental phase diagram BEDT-X

Phase diagram (X=Cu[N(CN)₂]Cl)
S. Lefebvre et al. PRL 85, 5420 (2000), P. Limelette, et
Layered organics (κ–BEDT-X family)

BEDT-TTF layer
Anion layer

$t \approx 50$ meV

$\Rightarrow U \approx 400$ meV

$t'/t \sim 0.6 - 1.1$
The glue
Im $\Sigma_{an}$ and electron-phonon in Pb

Maier, Poilblanc, Scalapino, PRL (2008)
The glue


The glue and neutrons

Wakimoto ... Birgeneau PRL (2007); PRL (2004)
\[ H(t) = -\sum_{ij\sigma} t_{ij} c_{i\sigma}^{\dagger} c_{j\sigma} e^{-i \int_{0}^{t} dr_{ij} \cdot A(r,t)} + U \sum_{i} n_{i\uparrow} n_{i\downarrow} \]

\[ \Delta_p = \frac{1}{V} \sum_{p'} U(p-p') \langle c_{-p'\downarrow} c_{p'\uparrow} \rangle \]

\[ |BCS(\theta)\rangle = \cdots + e^{iN\theta} |N\rangle + e^{i(N+2)\theta} |N+2\rangle + \cdots \]
The dream

http://www.physique.usherbrooke.ca/taillefer/Vulgarisation.html
To do

- Work with what we have
  - Quantum computer (SC vs laser)
- Improve theoretical methods
- Guide the search for new materials
  - AFM
  - U
  - There does not seem to be a fundamental law prohibiting room temperature superconductivity
- Design heterostructures
Main collaborators

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Kristjan Haule

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Massimo Capone
Réseau Québécois de Calcul de Haute Performance

Mammouth, série
Merci

Thank you