The High $T_c$ Superconductors: BCS or Not BCS?

Does BCS theory work for the high temperature superconductors?

We take a look at the electronic excitations using angle resolved photoemission spectroscopy (ARPES).
Outline

- Brief introduction to ARPES.
- The phase diagram: the underdoped and overdoped regions.
- Difference in behavior between these two regions.
Collaborators

A. Kanigel, U. Chatterjee, M. Shi, & J. C. C.
University of Illinois at Chicago &
Argonne National Laboratory

M. R. Norman, S. Rosenkranz, D. Hinks
Argonne National Laboratory

M. Randeria
Ohio State University

T. Takahashi
Tohoku University

K. Kadowaki
Tsukuba University

Helené Raffy, Z.Z. Li
Université Paris-Sud
The high temperature superconductors
Schematic phase diagram

Doping ($e^-/Cu$)

Strange metal (no qp)

Normal Metal

d-wave superconductor

$T^*$

$T_c$

How do we know all this?

In large part from angle resolved photoemission
Angle resolved photoemission

Why is ARPES important in the HTSC problem?

- Strong k-dependences in quantities of interest: SC gap; pseudogap; self-energy
- High temperature ($T_c \sim 100$K) & energy ($\Delta \sim 10$'s meV) scales
- High resolution $\delta k \sim 0.01 \ (2\pi/a)$, $\delta \omega \sim 5 - 15$ meV

Reviews:
The ARPES spectra

It provides a fairly complete view of the excitations

Slope: Velocity

$$v = \frac{dE}{dk}$$

Position: Energy

Width: 1/Lifetime

Each spectrum corresponds to a particular $k$
ARPES measures the spectral function $A(k, \omega) = -\frac{1}{\pi} \Im m G_R$

probability of adding or removing a particle from a many-body system

Randeria, et al., PRL 74 (95) 4951

Impulse approximation

$I \propto \left( \langle \psi_f | \vec{A} \cdot \vec{p} | \psi_i \rangle \right)^2 A(k, \omega) f(\omega)$

Depends on
• $k$
• polarization
• $\hbar \nu$
• * selection rules

Depends on
• $k$
• $\omega$
• $T$
• * sum rules
Eliminating the Fermi Function

\[ I(k, \omega) \propto A(k, \omega)f(\omega) \]

When all extraneous effects are removed, we are left with the single state crossing the Fermi energy.

PRB 52 (1995) 615

Campuzano, et al.,
PRL 64 (90) 2308
HTSCs: The Phase transition in the OD region.
HTSCs: The Phase transition in the OD region

Temperature \( \times 10^2 \text{K} \)

Doping

AFM

SC

0.04 0.12 0.2

\[ \Delta \text{(meV)} \]

Temperature (°K)

BCS

E(meV)

100 -50 0
How do we know we are looking at $\Delta$?

Particle-hole mixing

BCS

Campuzano, et al., PRB 53(96) R14797
Shape of the superconducting gap

Shen, et al. PRL 70, 1553 (93)
Ding, et el., PRL 73, 3302 (94)

$e^{-}$ along diagonal to Cu-O bond
not paired

phase sensitive experiments
van Harlingen (1993, 95)
Tsuei & Kirtley (1994, 95)
Beyond BCS: thermodynamic transition NOT mean field

Ding, et al., Nature 382, 51 (96)
Loeser, et al. Science 273, 325 (96)
Contrast the UD and OD regime

Pseudogap same as SC gap

Beyond BCS: SC state does NOT arise from a Fermi liquid
Pseudogap leaves behind Fermi arcs

SC state

PG state

$\Delta(\phi) / \Delta(0)$

$T = 40 \text{ K} \quad \Delta(0) = 43 \text{ meV}

T = 140 \text{ K} \quad \Delta(0) = 52 \text{ meV}$

Fermi Arc

Norman, et al., Nature 392 (98) 157
Scaling properties of the Fermi arcs

As the doping decreases, the Fermi arcs get shorter!
Scaling properties of the Fermi arcs

As the temperature decreases, the arcs also get shorter!
If you could go down to $T=0$ in the PG state, it would have four point nodes, just like a d-wave SC, but it's NOT a SC!
Are the Fermi arcs just a T-effect?

Beyond BCS: $\Delta$ shows NO T-dependence
Beyond BCS: NO relation between the gap and the order parameter!
Fermi arc collapse controlled by transition width

Kanigel, et al., PRL, 99, 157001 (07)
Pseudogap in parts like a metal and in other parts akin to a SC, but no LRO
Underdoped Bi 2212

Parabolic behavior at highest $T$ due to $\Delta \chi H_z$

Less than parabolic due to diamagnetism

$T_c$
**Properties of the pseudogap**

- PG same magnitude as $\Delta$.
- Anisotropy is $T$-dependent, leading to disconnected Fermi arcs below $T^*$.
- PG at same $k_F$ of the SC gap and of the normal state.
- Fermi arc collapses below $T_c$.
- There is fluctuating diamagnetism in the PG.

$\Rightarrow$ PG is a precursor to the SC gap.
Summary: What ARPES tells us

Phase diagram exhibits the failure of three paradigms of 20th Century Solid State Physics!

**Band theory**
- fails for the $x=0$ parent insulator

**Landau’s Fermi liquid theory**
- fails for the strange metal and pseudogap regimes

**BCS fails**
- for the Unconventional SC for $x<optimal$