The d-wave nodal liquid

Mike Norman

Materials Science Division
Argonne National Laboratory

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Phase Diagram of the Cuprates

- Temperature (Kelvin)
- Hole Doping (x)
- superconductor
- pseudogap
- Antiferromagnet
- spin glass
- "normal" state
- Fermi Liquid
- T*
- T_N
- T_c (T_coh)
- T_c (Tcoh)
What is the Pseudogap?

1. Spin singlets
2. Pre-formed pairs
3. Spin density wave
4. Charge density wave
5. d density wave
6. Orbital currents
7. Flux phase
8. Stripes
ARPES

(-- Antinode UD83K vs T

(\pi,0) UD85K vs T

Binding Energy (eV)

- $T < T_c$ (node)
- $T_c < T < T^*$ (Fermi arc)
- $T > T^*$ (full Fermi surface)
Gap closing with T (point 2) versus Gap filling with T (point 1)

Norman et al., PRB (1998)
Bi2212
OP90K
T=140K

Fermi function divided data along the Fermi surface

Fermi function divided data along the Fermi surface

E=0

Norman et al., PRB (2007)
MGL - minimum gap locus

SC gap

pseudogap

Bi813 (T_c=90K)

Bi2212, OP90K, T=140K
Kanigel et al., PRL (2008)
Is the $T=0$ limit of the pseudogap phase a nodal metal?

Nodal Liquid Implied by Low T Thermal Conductivity

Doiron-Leyraud et al., PRL (2006)
Nodes in LBCO, $x=1/8$

Collapse of Arcs Through $T_c$

Kanigel et al., PRL (2007)
Kanigel et al., PRL (2007)
\[ \Sigma = -i\Gamma_1 + \frac{\Delta^2}{(\omega + i\Gamma_0)} \]

where
\[ \Delta \] is the gap, \( \Gamma_1 \) the single particle scattering rate and \( \Gamma_0 \) the inverse pair lifetime

**Antinode vs T**

Norman *et al.*, PRB (1998)
Arc Length is Linear in $\Gamma_0 \rightarrow \Gamma_0 \sim T \rightarrow$ Arc Length $\sim T$
(lifetime broadened d-wave node)

Also explains arc collapse below $T_c$ ($\Gamma_0 \rightarrow 0$)

Norman et al., PRB (2007)
Pocket in Bi2212? (91K vs 65K)
Pocket in La doped Bi2201

Meng et al., arXiv: 0906.2682
Pocket in Nd-doped LSCO (x=0.12)

Two Gap Behavior in Bi2212 (underdoped)

Two Gap Behavior in Bi2201 (optimal doped)

Kondo et al., PRL (2007)
Two Gap Behavior in LBCO ($x=1/8$)

He et al., Nat. Phys. (2009)
Two Gap Behavior in LSCO ($x=0.15$)

Terashima et al., PRL (2007)
Single Gap Behavior in Bi2201 (optimal doped)
Single Gap Behavior in LSCO, $x=0.105$

Shi et al., arXiv:0810.0292
Universal “single gap” behavior

Chatterjee et al., unpublished
Arcs in STM

A

\[ k_y(\pi/a_0) \]

\[ k_x(\pi/a_0) \]

C

Arc length (%)

Temperature (K)

55K
45K
37K
30K
15K
4.5K

J. Lee et al., unpublished
Structural Umklappps in Bi2212