Low-Temperature Thermal Transport by Nodal Quasiparticles in the Cuprates:

Recent Results

M i c h a e l  S u t h e r l a n d
U n i v e r s i t y  o f  C a m b r i d g e

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Collaborative Networks – High quality single crystals......

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Universal heat transport by nodal quasiparticles

This result is universal with respect to impurity concentration.

Robust to vertex and Fermi liquid corrections.

Electronic heat transport provided solely by quasiparticles ($T \rightarrow 0$, $T \ll \gamma \ll \Delta_0$)

$$\kappa_0 = \frac{k_B^2}{3\hbar} n \left(\frac{v_F}{v_2} + \frac{v_2}{v_F}\right)$$


Fermi Surface

Nodal Quasiparticles

Nodal excitation spectrum:

$$E = \hbar \sqrt{v_F^2 k_1^2 + v_2^2 k_2^2}$$

density of states

$\gamma$ impurity bandwidth

$N(E)/N_0$
Evidence for universal heat transport in cuprates

0.6% Zn doping changes elastic scattering rate by a factor of 10.
The overdoped regime - $\text{Tl}_2\text{Ba}_2\text{CuO}_{6+\delta}$

$\frac{T_c}{T_c^{\text{max}}} = 1 - 82.6(p - 0.16)^2$

$\kappa_0/T \propto V_F/V_2 \propto 1/\Delta_0$

No longer in the limit ($T \ll \gamma \ll \Delta_0$)

$\gamma \sim \Delta_0 \sim 2-3$ meV

Tunneling data: N. Miyakawa et. al. PRL 83, 1018 (1999).
The underdoped regime

\[ \kappa_0/T \text{ decrease as doping} \]

\[ v_F/v_2 \text{ decrease as doping} \]

\[ YBa_2Cu_3O_x \]

\[ T^2 [K^2] \]

\[ \kappa[T] [mW/K^2cm]\]


ARPES data: XXX et. al. PRL 83, 1018 (1999).
YBa$_2$Cu$_4$O$_8$ is a naturally underdoped ($T_c \sim 80$K) cuprate with full double chains.

Absence of residual linear term ($k_0/T \sim 0$)

YBa$_2$Cu$_4$O$_8$ : a stoichiometric underdoped cuprate

Stoichiometric compound

→ Exceptionally clean crystals, no oxygen vacancy disorder.
→ No twinning

YBa$_2$Cu$_4$O$_8$ is a naturally underdoped (T$_c$ ~ 80K) cuprate with full double chains.

Finite residual linear term ($k_0/T$~0.18mW/K$^2$cm)

Downturn in low temperature data...
... understood to be related to contacts


M. Sutherland et al, unpublished (2006)
The extreme underdoped regime (p near $p_{SC}$)

Superconducting state, $T_c \sim 6$K

$\text{YBCO}_{6.33}$ - Finite residual linear term
The extreme underdoped regime

non-superconducting state, no sign of $T_c$ in resistivity to 50mK

YBCO$_{6.31}$

Finite linear term appears confined to region near $p_{sc}$

Finite temperature data

Difference in data sets evolves as:

\[ T^3 \] (low dopings \( p < p_{SC} \))

negligible (\( p > p_{SC} \))

Additional Bosonic excitation, low doped YBCO

\[ \beta = \frac{1}{3} C v \ell \]

Due to:
- phonons?
- magnons?
- ...?
Conclusions

- Existence of Delocalized Fermionic excitations in the normal state YBCO (small range near $p_{sc}$).
- Additional Bosonic mode onsets near $p_{sc}$.

- Extreme underdoped regime

- Moderately underdoped-overdoped regime

- Thermal transport well described by d-wave BCS theory.
Conclusions

- Existence of **Delocalized** Fermionic excitations in the normal state of ultra-pure YBCO
- **Thermally metallic** ground state near $p_{SC}$

**Bosons - Additional $T^3$ term**

- Growth of a **bosonic** mode ($T^3$ term in kappa) **below** $p_{SC}$
- Onset of mode occurs at $p = p_{SC}$
Beyond the $T^3$ approximation

Specular Reflection of Phonons

Sapphire

Specular reflection $I_{ph} = f(T)$

$\kappa_{ph}/T \sim T^\alpha$, $\alpha < 2$

Fit data to

$\kappa/T = \kappa_0/T + BT^\alpha$

$\kappa_0/T = 0$

$V_3Si$ s-wave SC

(thermal insulator, $\kappa_{el} = 0$)

$\alpha = 1.7$

R. O. Pohl* and B. Stritzker, PRB 25, 3608 (1982).
Neutron Scattering, low doped LSCO

Evolution of magnetic Bragg peak follows the expected field dependence of SDW order.

Low doped LSCO is SDW+dSC

The Cuprate Phase Diagram Elucidated by Thermal Conductivity: LSCO

H > 0

***See poster by Shiyan Li***

Evidence for a normal state metal-to-insulator transition near \( p \sim 0.15 \) in LSCO

SC-insulator transition (0 field) near \( p \sim 0.05 \)
The Cuprate Phase Diagram Elucidated by Thermal Conductivity: YBCO

Delocalized Fermions

D-wave superconductor (nodal quasiparticles)

H > 0

Unlike LSCO, field drives YBCO towards a thermally conductive ground state.

Neutron Scattering, μSR in YBCO

No long range SDW order.

Coexistence of short range AF and dSC?


No long range SDW order.

Slowly fluctuating spin clusters?

Low doped YBCO is dSC + (some sort of) magnetism

C. Stock et. al. cond-mat/0505083
- Additional **Bosonic** thermal conductivity which vanishes at $p=0.05$
  - Ungapped acoustic magnon?
  - Fundamental excitation of a charge ordered state?

- Existence of **delocalized** Fermionic excitations in the normal state, with the **same** conductivity as the SC state.

- Normal state near $p=0.05$ **violates** WF law, with violation **growing** as doping is lowered.
  - Spin charge separation?