Nernst effect and diamagnetism in cuprates: Vortex or quasiparticle?

- The upper critical field $H_{c2}$ in hole-doped cuprates
- Onset of pairing above $T_c$
- The carrier sign of the FS pocket. How many pockets?
- Time-reversal invariance breaking in LBCO-1/8

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1. The upper critical field in hole-doped cuprates $H_{c2}$

2. The onset temperature of vortex liquid

3. The sign of small FS pocket? How many pockets?

4. Time-reversal invariance breaking in striped cuprate LBCO
Magnetization, Nernst and upper critical field

Mean field

Type II magnetization

Vortex Nernst effect

\[ M \]

\[ H_c^2 \]

\[ H_c^1 \]

\[ v \]

\[ E = B \times v \]

\[ \nabla T \]
Nernst signal $e_N$ and Magnetization give same $H_{c2}$ (to 10%)
Two contrasting views of UD cuprates

- Vortex liquid
- $\Delta_{\text{max}}$ finite
- Phase disorder

- Normal state
- No vortices

Onset of resistance

$H_{c2}$
In LSCO, $H_{c2}$ has largest value near 1/8 (>80 T)
Resistive and thermopower transition occurs at vortex-solid melting $H_{\text{melt}} \ll H_{c2}$ in LaSrCuO.

Nernst, resistivity

Thermopower

Magnetization

Wang, Li, NPO PRB ’06, and *unpub.*

Li et al, PRB 2010

Resistive and thermopower transition occurs at vortex-solid melting $H_{\text{melt}} \ll H_{c2}$.
Magnetization in OPT and UD Bi 2212 $\rightarrow H_{c2} > 150$ T

Li et al, PRB 2010

Bilayer cuprates have very large $H_{c2}$ (100-150 T)
Confusion between $H_{\text{melt}}$ and $H_{c2}$ in Ortho-II YBCO ($y=6.50$)?

Nernst signal implies $H_{\text{melt}} = \sim 30 \text{ T at } 1 \text{ K, but } H_{c2} > 100 \text{ T.}$

Resistance onset lies on the melting line.
Hc2 from Hall resistance and collapse of magnetic hysteresis in UD YBCO?

Taillefer *et al.*, Nature 2007

- Resistive transition

Jaudet, Proust *et al.*, PRL '08

Paramagnetic?

Resistive transition and $H_{irr}$ suggestive of normal state and interpreted as $H_{c2}$
We divide torque by $H$ to get $M$
(data of Jaudet, Proust et al. PRL ‘08)

In UD YBCO, hysteresis vanishes at $H_{\text{melt}}$, but diamagnetism extends to above 60 T
Square-root background term arises from Volovik (doppler shift) effect.

Condensate survives to fields > 45 Tesla.

Oscillations are from a single FS pocket
1. The upper critical field in hole-doped cuprates $H_{c2}$

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Cyr-Choiniere, Taillefer et al. Nature 2009
Torque Signal in underdoped Bi 2212 ($T_c = 50$ K)

$\tau = m \times B$

Diamagnetic signal extends above $T_c$ to $\sim 100$ K

Wang et al.
PRL 2005
Onset of diamagnetic component in UD and OP Bi 2212

Diamagnetic component onsets above 100 K in UD and OP Bi2212.

Absent in LSCO (0.05) above 25 K.

Wang et al. PRL 05
High onset temperature in series of Bi 2212 and LSCO crystals
Phase diagrams of LSCO and Bi 2201

Lu Li et al, PRB ‘10

$T_{\text{onset}}$ from Nernst and Torque expts. are consistent
Magnetization curves in optimal YBa$_2$Cu$_3$O$_7$ ($T_c = 92$ K)

In OPT YBCO, diamagnetic region (vortex liquid) extends to 120 K

Lu Li et al, PRB ‘10
Nernst and diamagnetism in striped cuprate LaBaCuO $x = 0.125$

Li, Alidoust, Tranquada, Gu, Ong, preprint

Onset of pairing in Nernst signal at 100 K agrees with diamagnetic susceptibility (BNL)

Hücker, Gu, Tranquada, PRB '08

Diamagnetic signal observed in susceptib. $\chi_c$
Visualizing pair formation on the atomic scale in the high-\(T_c\) superconductor \(\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8+\delta\)

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Gapped regions lose connectivity near 120 K \(\sim T_{\text{onset}}\)
Spectroscopic Fingerprint of Phase-Incoherent Superconductivity in the Underdoped Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$

Lee, Fujita, Schmidt, Kim, Eisaki, Uchida and Davis

Science (2009)

- UD Bi-2212 with $T_c = 37$K
- QPI of the particle-hole symmetric Bogoliubov qp
- No change observed in the octet QPI pattern across $T_c$
- Survives to 1.5 $T_c$
- State above $T_c$ has phase-disordered Cooper pairing
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Electron pockets in the Fermi surface of hole-doped high-$T_c$ superconductors

Vortex velocity gives *negative* Hall conductivity in UD, OP hole-doped

\[ E = B \times v \]

Vortex vel. gives *positive* Nernst signal but *negative* thermopower
Melting of vortex solid adds a large negative Hall current.

At low temp., vortex Hall current dominates so $\rho_{xy} < 0$.

Additivity of conductivity tensors allows separation

$$\sigma_{xy} = \sigma_{v_{xy}} + \sigma_{qp_{xy}}$$

$$\sigma_{v_{xy}} \sim 1/H \quad (negative)$$

$$\sigma_{qp_{xy}} \sim H \quad (positive)$$

Vortex flow strongly distorts observed Hall effect in cuprates
Origin of negative Hall signal below $T_c$?

Flux flow Hall is negative in all hole-doped cuprates (except very OD)

Hall effect *dominated* by vortex $\sigma_{xy}$
Seeing QP without vortices: Thermal Hall Effect $\kappa_{xy}$

\[
\begin{pmatrix}
J_x^Q \\
J_y^Q
\end{pmatrix} =
\begin{bmatrix}
\kappa_{xx} & \kappa_{xy} \\
\kappa_{yx} & \kappa_{yy}
\end{bmatrix}
\begin{pmatrix}
-\partial_x T \\
-\partial_y T
\end{pmatrix}
\]

Semiclassical picture

Vortex-scattering picture

Lorentz force deflects Bogolyubov QP

$\kappa_{xy}$ results from lower energy of path circumventing core against $J_s$ (Volovik Doppler shift)

$K_{xy}$ is sensitive to quasi particles only; \textit{Insensitive} to vortex current
In UD YBCO, no evidence for negative QP to 7.5 K and 14 T
Assume there is no vortex current

Consider a two-band system with high-mobility electrons and low-mobility holes ($\mu >> \nu$), and $p > n$ (larger hole population).

For $\mu B, \nu B >> 1$, the Hall conductivities $\sigma_{xy}$ decrease as $1/(\mu B)^2$.

The slower, more populous holes dominate total Hall conductivity.

In complex representation ($\sigma_{xx} = Re \hat{\sigma}$, $\sigma_{xy} = Im \hat{\sigma}$)

$$\hat{\sigma}^e = \frac{ne\mu}{1 + i\mu B}, \quad \hat{\sigma}^h = \frac{pe\nu}{1 - i\nu B}.$$ 

$$\hat{\rho}(p) = \left[ \frac{pe}{\nu^2 B} + \frac{ne}{\mu^2 B} + i\frac{e}{B} (p - n) \right]^{-1} (\mu B, \nu B \gg 1).$$

In high-field limit, high-mobility electrons are in tight cyclotron orbits. Their $\sigma_{xy}$ is strongly reduced.
Thermopower displays jump at $H_{\text{melt}}$
In YBCO, $S$ is negative along chain axis $b$, but positive along axis $a$.

Sign anisotropy in $S$ $\rightarrow$ large anisotropy in Nernst is a simple band effect

$$E_y = [\alpha_{xy} \rho - \rho_{yx} \alpha](-\partial T)$$
$$= [\alpha_{xy} \rho - \text{Stan} \theta_H](-\partial T)$$

changes sign btw. $a$ and $b$

Caution on interp. of Nernst anisotropy as "Nematicity"
Appearance of pocket correlates with suppression of $T_c$ and condensate stiffness

Is FS pocket good for high $T_c$?

Max. $T_c$ suppression and largest QP Nernst signal occur at $y = 6.63$
$H_{c2}$ vs $T_{onset}$ in single-layer cuprates

$H_{c2}$ torque magnetization scales linearly with $T_{onset}$

Fit to

$$2\left(\frac{g}{2}\right)\mu_B H_{c2} = k_B T_{onset}$$

gives $g = 2.2$

Clogston limit determines $H_{c2}$

Lu Li et al., unpubl.
Questions

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Anomalous Nernst signal in LBCO-1/8

Li, Alidoust, Tranquada, Gu, Ong, preprint
Summary

1. Onset of $R$ and $S$, and vanishing of hysteresis occur at by $H_{\text{melt}}$, not $H_{c2}$

2. $H_{c2}$ is much higher (> 100 Tesla) in UD YBCO

3. Onset of pairing at $T_{\text{onset}}$ determined by torque and Nernst

4. No evidence for negative sign of QPs from Hall

5. Heat capacity points to only 1 pocket

6. Resistivity tensor is a poor diagnostic of vortex liquid and $H_{c2}$
How many quasi-particle pockets in the normal state? – Reconstruction??

\[ C \,(H=0) = \gamma T + \beta T^3 \]

where in 2D, \( \gamma_m = \gamma' (|n_\alpha| m_\alpha^* + |n_\beta| m_\beta^*) / m_e \)

\[ \gamma' = 1.46 \text{ mJ mol}^{-1} \text{K}^{-2} \]

If \( \alpha \) pocket is electrons at \((0, \pi)\) and \( \beta \) pocket is holes at \((\pi/2, \pi/2)\),

\[ |n_{\alpha}| = 2 \quad m_\alpha \sim 1.3 \, m_e \]
\[ |n_{\beta}| = 4 \quad m_\beta \sim 3.8 \, m_e \]

then \( \gamma_{el} \) should be \( \sim 26 \) mJ/mol-K


OBSERVED SPECIFIC HEAT IS DRAMATICALLY TOO SMALL FOR THIS PROPOSED RECONSTRUCTION

\[ \gamma_{el}(0T) \sim 1.9 \text{ mJ/mol-K}^2 \quad \gamma_{el}(45T) \sim 5.3 \text{ mJ/mol-K}^2 \quad \gamma_{el}(45T - 0T) \sim 3.1 \text{ mJ/mol-K}^2 \]
Lu Li et al., PRB ‘10

In Bi 2201
Diamagnetic $M_d$ survives to $H > 45$ T
Magnetization curves in underdoped Bi 2212

Wang et al. PRL 2005

Diamagnetism curves not textbook mean-field, not Gaussian

Diamagnetic response extends to >90 K ($T_c = 50$ K).

Fragile London rigidity regime above $T_c$. 
Phase diagram in $H$-$T$ plane

Mean-field phase diagram

- $2H$-NbSe$_2$
- $H_m$
- $H_{c1}$
- $H_{c2}$
- normal
- liquid
- vortex solid
- Meissner state
- $T_c = 7$ K
- $T_c = 100$ K

Cuprate phase diagram

- $H_{c2}$
- $H_m$
- vortex liquid
- vortex solid
- Vortex unbinding in $H = 0$
Deconstructing the Specific Heat

Resistive Transition at $H_{\text{irr}} = 25T$

No saturation at high fields!

Total Signal

$\gamma(H) \text{ mJ mol}^{-1} K^{-2}$

Magnetic Field, $H(T)$

Resistive Transition at $H_{\text{irr}} = 25T$

No saturation at high fields!

$H_{\text{irr}} \sim 25T$

(Total Signal) – (Nodal Quasiparticles)

$H_{\text{irr}} \sim 25T$
Doppler Shift (Volovik effect) and paramagnetic current

- Supercurrent is accompanied by paramagnetic back-flow.
- Large superfluid vs shifts QP energy $E(k)$
- Shift is pronounced at nodes of Dirac cones in d-wave superconductors.
- QP DOS increases as (Volovik)

$$DOS \sim \sqrt{B}$$
- Condensate amplitude persists to $T_{onset} > T_c$
- Nernst signal confined to SC dome
- Vorticity defines Nernst region