Magnetization in Vortex-Liquid State in Cuprates

Lu Li, J. G. Checkelsky, N.P.O. *Princeton Univ.*
Yayu Wang, *Princeton U., U.C. Berkeley*
M. J. Naughton, *Boston College*
S. Ono, S. Komiya, Yoichi Ando, *CRI, Elec. Power Inst., Tokyo*

1. Vortex Nernst effect
2. Diamagnetism
3. Phase diagram
4. Low-temp. Vortex Liquid State

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Pseudogap state in hole-doped cuprates

Phase rigidity

\[ |\Psi| = e^{i\theta(r)} \]

Pairing anomalously strong

Phase rigidity soft

Spontaneous vorticity destroys rigidity and Meissner state
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

**Cuprate phase diagram**

- $H_{c2}$
- $H_{m}$
- Vortex solid
- Vortex liquid
- $T_{c}$
- $T_{c0}$
- 7 K
- 100 K
- Vortex unbinding in $H = 0$
Magnetization in Abrikosov state

\[ M = - \left[ H_c^2 - H \right] / \beta (2\kappa^2 - 1) \]

In cuprates, \( \kappa = 100-150 \), \( H_{c2} \approx 50-150 \) T

\( M < 1000 \text{ A/m (10 G)} \)

Area = Condensation energy \( U \)
Phase rigidity $\rightarrow$ uniform phase $\theta$

$$|\Psi| \ e^{i\theta(r)}$$

$$H_\rho = \frac{1}{2} \int d^3 r \ \rho_s (\nabla \theta)^2$$

phase rigidity measured by $\rho_s$

But phase coherence destroyed by mobile vortices

$$\Delta \theta = 2\pi$$
Contour Map of Nernst Signal in Bi 2201

![Contour Map](image)

- **Bi-2201 (La:0.4), $T_c=28K$**
- **$e_y (\mu V/K)$**
- **$\mu_0 H (T)$**
- **$\mu_0 H (T)$**
- **$T (K)$**
- **$H_{c2}$**
• Condensate amplitude persists to $T_{\text{onset}} > T_c$
• Nernst signal confined to SC dome
• Vorticity defines Nernst region
Implications of Nernst signal

1. Vorticity persists high above $T_c$

2. Confined to SC “dome”

3. Loss of long-range phase coherence at $T_c$
   by spontaneous vortex creation (not gap closing)

4. Vortex-liquid state persists deep into pseudogap State

5. Pseudogap state distinct from phase fluc in Lightly-doped regime.

Thermodynamic evidence from diamagnetic response
Supercurrents follow contours of condensate

\[ \mathbf{J}_s = -(e\hbar/m) \nabla \mathbf{x} |\Psi|^2 \hat{\mathbf{z}} \]
Micro-fabricated single crystal silicon cantilever magnetometer

- Si single-crystal cantilever
- Capacitive detection of deflection
- Sensitivity: \( \sim 5 \times 10^{-9} \) emu at 10 tesla
  \( \sim 100 \) times more sensitive than commercial SQUID
Torque magnetometry

Torque on moment: \( \tau = m \times B \)

Deflection of cantilever: \( \tau = k \phi \)
Torque magnetometry

Spin moment $m_p$

$$\tau = m_p \times B + MV \times B$$

2D supercurrent

$$\frac{\tau}{V} = \chi_c H_x B_z - \chi_a H_z B_x + M B_x$$

$$M_{\text{eff}} = \frac{\tau}{VB_x} = \Delta \chi_p H_z + M(H_z)$$

Exquisite sensitivity to 2D supercurrents
Mysterious $A_1\sin2\theta$ term!

FIG. 4. Typical angular dependence of the torque density for the crystals investigated in this work. In all cases, $T/T_c=0.85$ and $H = 5$ T. The solid curves are the fits according to Eq. (3).
• In underdoped Bi-2212, onset of diamagnetic fluctuations at 110 K
• diamagnetic signal closely tracks the Nernst effect
Torque Signal in underdoped Bi 2212

Wang et al.
PRL 2005
Paramagnetic van-Vleck background in Bi 2212 and LSCO
Magnetization curves in underdoped Bi 2212

Wang et al.
PRL 2005
At high $T$, $M$ scales with Nernst signal $e_N$

Confirms vortex origin of Nernst signal
Comparison of $M$ vs $H$ with Nernst signal in OP and UD Bi 2212
Above $T_c$, $M/H$ is singular

$M \sim -H^{1/8}$ ($\chi$ divergent as $H \to 0$)
$M \sim H^{1/6}$

$M$ non-analytic in weak field
Non-analytic magnetization above $T_c$

$M \sim H^{1/\delta}$

Fractional-exponent region

LuLi et al. EuroPhys 2005
Fit to Kosterlitz Thouless theory

\[ \chi = -(k_B T/2d\phi_0^2) \xi_{KT}^2 \]

\[ \xi_{KT} = a \exp(b/t^{1/2}) \]

Strongly H-dependent Susceptibility \( \chi = M/H \)
$H_{c2}$ is not linear in $(1-t)$, not BCS scenario
Calculated diamagnetic response of Kosterlitz-Thouless superconductor

Wang et al., PRL '05
\[ M = - \frac{[H_{c2} - H]}{\beta(2\kappa^2 - 1)} \]

Lu Li et al., unpubl.

**Hc2 nearly T independent**
The graph shows the magnetization $M$ (A/m) as a function of the magnetic field $\mu_0 H$ (T) for different temperatures: 40 K, 50 K, 60 K, and 70 K. The material is Bi 2212, with a transition temperature $T_c = 87.5$ K.
Problems with Flux-flow Resistivity

Resistivity does not distinguish vortex liquid and normal state

Bardeen Stephen law (not seen)  
Wang, Li, NPO PRB '06
$H_{c2}$ 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.
In hole-doped cuprates

1. Large region in phase diagram above $T_c$ dome with enhanced Nernst signal

2. Associated with vortex excitations (not Gaussian)

3. Confirmed by torque magnetometry

4. Transition at $T_c$ is 3D version of KT transition (loss of phase coherence)

5. Depairing field $H_{c2}$ anomalous in $T$ dependence,

6. Scales linearly with $T_{onset}$
Very lightly doped limit in LSCO

The phase diagram in x-H plane at low T?
As-observed torque magnetization results in 6 LSCO xtals

Lu Li et al., unpubl.
Magnetization in lightly doped La$_{2-x}$Sr$_x$CuO$_4$

Lu Li et al., Nature Phys

Evidence for robust diagmagnetism for $x < x_c$
Magnetization curves in very lightly-doped LSCO

Diamagnetism persists to 3 percent doping
Vortex liquid stable at 0.3 K
Cooper pair competes with local moment formation
$M_{\text{obs}}$ is comprised of diamagnetic and paramagnetic terms

Lu Li et al., unpubl.
Ground state
Comparison between $x = 0.055$ and $0.060$

Lu Li et al., Nature Physics ‘07

Pinning current reduced by a factor of $\sim100$ in ground state
Vortex solid-to-liquid transition for $x < x_c$  

Debye Waller dependence  

$$H_m(T) = H_0 \exp(-T/T_0)$$
Low-Temperature $H$-$x$ Phase Diagram

Lu Li et al., Nature Physics ‘07
T-H-x phase diagram of LaSrCuO in UD regime
$d$-wave duality near Mott limit


\[ L_{QQL}^d = \gamma_t |\dot{\Psi}|^2 + \gamma |(\nabla - i(2e)A)\Psi|^2 + \alpha |\Psi|^2 + \frac{1}{4} |\Psi|^4, \]
Low-temperature vortex liquid

1. Vortex solid surrounded by vortex liquid at 0.35 K

2. Sharp quantum transition at $x_c = 0.055$. Quantum vortices destroy phase coherence

3. At 0.35 K, pair condensate survives without phase rigidity even for $x = 0.03$

4. Melting of vortex solid appears to be classical at 0.35 K (Debye-Waller like).
Other Experimental Techniques

1. Kinetic inductance at THz freq in Bi 2212 (Orenstein, Nature ‘99)
2. Thermal expansion YBCO (Meingast, PRL ‘00)
3. Magnetization Bi 2212, LSCO, Bi 2201 (Wang, Li, PRL, EPL ‘05)
4. STM above Tc Bi 2212 (Yazdani, Nature ‘07)
5. ARPES?

Other Superconductors

1. CeCoIn$_5$ (Matsuda-Behnia, PRL ‘05), corrected (Onose, NPO, Petrovic EPL ‘07)
   Large Nernst signal 13 K above Tc (2.3 K)

2. Organic superconductor $\kappa$-(BEDT-TTF)$_2$-$X$
   (Nam, Ardavan, Blundell, Schlueter preprint ‘07)
   Nernst signal 6 K above Tc (12 K) near Mott trans.

3. Nb$_{1-x}$Si$_x$ (Behnia et al, NaturePhys 06), 2D Gaussian fluct.?
References (Talk 3)


Summary

1. Nernst region is suffused with vorticity, enhanced diamagnetism and finite pairing amplitude

2. Extends from $T_c$ to $T_{\text{onset}} < T^*$

3. Nernst region *dominates* lower temp part of Pseudogap state

4. Depairing field $H_{c2}$ and binding energy are very large

   Pairing (diamagnetism) persists to 0.03

5. Vortex-liquid state is ground state below $x_c$
<table>
<thead>
<tr>
<th>Pre- and Post-amble</th>
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<tbody>
<tr>
<td>• Baskaran, Zou, Anderson (Sol. St. Comm. 1987)</td>
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<td>• Doniach, Inui (PRB 1989)</td>
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<td>• Uemura plot (Nature 1989)</td>
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<td>\textit{low hole density and high Tc}</td>
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<td>cuprates highly susceptible to phase fluctuations</td>
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<td>• Corson, Orenstein (Nature 1999)</td>
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<td>\textit{Kinetic inductance meas. at THz freq extends above Tc}</td>
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<td>KT physics in ultra-thin film BSCCO</td>
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<td>• M. Franz and Z. Tesanovic (1999)</td>
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<td>\textit{Vortex-charge duality, QED3 model}</td>
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<td>• A. Vishwanath, Raghu (2006) \textit{Simulation 2DXY}</td>
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<td>• Sachdev (2007) \textit{AdS-CFT duality technique}</td>
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<tr>
<td>• Tesanovic (2007) Quantum vortices</td>
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Vortex-liquid state at limit $T \to 0$

1. Large diamagnetism ($0.03 < x < 0.06$)

2. Electrically insulating (in LSCO)

3. Pairing energy ($H_{c2}$) very large

4. Pairing coexists with
   weak background paramag. moment ($0.01 \mu_B$/cell)

5. Long-range phase coherence transition vs $x$ very sharp

6. Incompatible with cluster of supercond. droplets
M vs H below Tc

Lu Li et al. Europhys Lett 2005

Strong Curvature!

Full Flux Exclusion

Hc1
Meissner curves measured after zero-field cooling

- $M_d$ (A/m)
- $T_c$ for $H = 10$ Oe
- $x = 0.070$
Strong correlation in CuO$_2$ plane

\[ H = -t \sum_{i,j,\sigma} c_{i\sigma}^+ c_{j\sigma} + U \sum_i n_{i\uparrow} n_{i\downarrow} \]

\[ t = 0.3 \text{ eV}, \quad U = 2 \text{ eV}, \quad J = 4t^2/U = 0.12 \text{ eV} \]
Onset of diamagnetic signal at 5 Tesla
Strong correlation in CuO$_2$ plane

\[ \text{Cu}^{2+} \]

Large U

charge-transfer gap $\Delta_{pd} \sim 2$ eV

Mott insulator

best evidence for large U

antiferromagnet $J \sim 1400$ K

doping

\[
H = -t \sum_{i,j,\sigma} c^+_i \sigma c_{j\sigma} + U \sum_i n_{i\uparrow} n_{i\downarrow} \quad \text{Hubbard}
\]

\[
t = 0.3 \text{ eV}, \quad U = 2 \text{ eV}, \quad J = 4t^2/U = 0.12 \text{ eV}
\]
$M(T, H)$ matches $e_N$ in both $H$ and $T$ above $T_c$
Non-analytic magnetization
M vs H below Tc

Full Flux Exclusion

Strong Curvature!

Hc1

- M

H

(a)

(b)
$H = 14 \ T$

$M_{\text{tot}} (\text{A/m})$

$T (\text{K})$

UD, OD, OP

$T_{\text{onset}}$

$T_c$
Direct measurements of uniform susceptibility $\chi_c$ and $\chi_{ab}$
Torque \( \tau = A' H^{1+\alpha}, \) \( (\alpha < 1) \)
Strong correlation in CuO$_2$ plane

$\begin{align*}
    H &= -t \sum_{i,j,\sigma} c_{i\sigma}^+ c_{j\sigma} + U \sum_i n_{i\uparrow} n_{i\downarrow} \\
    t &= 0.3 \text{ eV}, \quad U = 2 \text{ eV}, \quad J = 4t^2/U = 0.12 \text{ eV}
\end{align*}$
Selective gap suppression in d-wave

At field $H_{c2}$ (or $T_{onset}$), pairs in dispersive region destroyed. Gap in antinode region survives.