Heterogeneous vortex dynamics in high temperature superconductors

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- Superconductivity
- Model NMR experiments
- Shear viscosity of the vortex liquid

2 Methods

- Experimental procedures
- Verification: bulk or surface properties?
- Magneto-optical imaging and transport measurements

3 Results

- Comparison with 2D melting model
- Comparison with 3D Bose-glass model

4 Discussions



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Superconductivity

Zero resistance and diamagnetism



Perfect conductivity.

Exclusion of magnetic field (known as the Meissner effect).

Superconductivity is a thermodynamic state.

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Superconductivity

Superconducting materials

- Many materials become superconducting at low temperatures or high pressures.
- New" discoveries:
 - cuprate family: YBCO (1987), BSCCO (1988),
 - boron-doped group-IV semiconductors (diamond, silicon, ...) (since 2001)
 - FeAs-based superconductors (2006)
 - SiH₄ (2008, under high pressure)
- Future: new forms of superconductivity?

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Two types of superconductors



In general, type-II superconductors have much higher H_c , J_c and also T_c than type-I superconductors. Here, we study type-II superconductors.

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Magnetic flux quantization

Magnetic flux quantification in type-II superconductors \Rightarrow vortices

$$B = n\phi_0, \ \phi_0 = \frac{h}{2e} = 2.07 \times 10^{-7} \text{ G} \cdot \text{cm}^2.$$



Vortex lattice observed in $Bi_2Sr_2CaCu_2O_x$ with micro Hall probes, $H_{//c} = 12$ Oe, T = 81 K. A. Grigorenko et al., Nature **414**, 728 (2001). Introduction Methods

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Superconductivity

Vortex distribution in real superconductors

- An ideal vortex lattice yields $j_c = 0$, $R \neq 0$. j_c is the critical current.
- Vortex pinning by material defects (pinning centers) ⇒
 Vortex distribution is no longer uniform ⇒ *j_c* > 0, *R* = 0.
- Bean's bulk pinning model (1962).

 $\frac{dB_z}{dz} - \frac{dB_z}{dx} = \mu_0 j,$ where $j = j_c$, $-j_c$ or 0.

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Nonuniform vortex distribution observed by MOI: bulk pinning

Magneto-optical imaging (MOI) measures the averaged flux density.

Image intensity gradient $\sim j_c$.

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T = 11.6 K, Field increasing

100 Oe

full penetration

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10 Oe

mm





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Magneto-optical images of a NbN thin film $(T_c = 14 \text{ K})$ with a thickness of 76 nm (deposited on a 12 nm thick Pt-Co layer with Si as the substrate).



Magneto-optical image of a YBa₂Cu₄O₈ single crystal, acquired at T = 10 K and $H_0 = 180 \text{ Oe}.$

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Even in the absence of bulk pinning, there is still a surface barrier.

Once vortices overcome the barrier, they accumulate in the center of the sample, yielding a dome profile.

Weak surface pinning, strong bulk pinning \Rightarrow Bean's profile.

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NMR

Influences of bulk pinning and surface barrier to other measurements Example: Nuclear Magnetic Resonance (NMR)

Inhomogeneous field distribution!

Questions:

- Is all the sample probed by NMR experiments?
- Supercurrent affects the density of states and thus the NMR Knight shift data. Is this influence important?

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Method to obtain ac current distribution


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Differential image acquisition procedure

YBa₂Cu₄O₈

y (axis a)



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ac current distribution in $YBa_2Cu_4O_8$ ($T_c = 82$ K)

Three regimes

- negligible screening current (T > 70 K)
- surface barrier flow (20 K < T < 70 K)</p>
- bulk pinning flow (T < 20 K)</p>

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Results: ac field penetration

Only the regions where the ac field penetrates are probed by NMR measurements.

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Discussions

Questions:

- Is all the sample probed by NMR measurements?
- Supercurrent affects the density of states and thus the NMR Knight shift data. Is this influence important?

Answers obtained from our NMR model experiment:

• At low temperatures (bulk pinning regime), only the sample edges are probed by NMR measurements.

For certain materials whose j_c is large, the supercurrent may affect the NMR Knight shift data.

 At intermediate temperatures (surface barrier regime), only the sample bulk is probed.

There may be a tiny K_s due to the current at the edges only.

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High temperature superconductors

New paradigm (\sim 1989): existence of a vortex liquid state.

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High temperature superconductors





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New paradigm (\sim 1989): existence of a vortex liquid state.

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Vortex lattice melting in BSCCO



vortex lattice melting:

- jump in vortex density.
- $R \rightarrow 0$.

However, pinning centers do not disappear!

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Resistance appears at vortex lattice melting

- In 2D: by the appearance of free vortex lattice dislocations. Resistance is related to the free dislocation density (Nelson-Halperin theory).
- In 3D: unclear. Is plastic motion of vortex lines important?

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How to measure the shear viscosity?

Method

Introduce artificial shear flow in weak pinning channel between strong pinning walls.

Hydrodynamic description

$$-\gamma \mathbf{v} + \eta \bigtriangledown^2_{\perp} \mathbf{v} + \mathbf{f} = \mathbf{0}$$

Result

$$\rho = \rho_f [1 - \frac{2\delta}{L} tanh(\frac{L}{2\delta})]$$

when $\delta(T) \equiv \sqrt{\eta/\gamma} >> L$, one has:

$$ho(\mathbf{T}) \sim \mathbf{B}^2 rac{L^2}{\eta(\mathbf{T})}$$

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But surface barrier problem ...

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Signature of surface barrier

Nonlinear resistance in the liquid vortex state.

Normalized R(T) of the square and strip crystal in the vicinity of the first order transition at $H_{//c} = 300$ Oe and with 10 mA current.

Measurements performed on $Bi_2 Sr_2 CaCu_2 O_8$ single crystals.

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Shear property

Signature of surface barrier in transport D. T. Fuchs et al., Phys. Rev. Lett. **81**, 3944 (1998)



Signature of surface barrier

Nonlinear resistance in the liquid vortex state.

Normalized R(T) of the square and strip crystal in the vicinity of the first order transition at $H_{//c} = 300$ Oe and with 10 mA current.

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Objective

Bulk viscosity measurements without surface barrier.

Method

Contacts and channel structure are remote from the sample edges. Furthermore, the contacts are heavily irradiated in order to *attract* the current.

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- Model NMR experiments
- Shear viscosity of the vortex liquid

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Experimental procedures

- Verification: bulk or surface properties?
- Magneto-optical imaging and transport measurements

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Selection of BSCCO single crystals

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Realization of channel structure through irradiation

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Realization of electrical contacts for transport measurements

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Sample preparation

Selection of BSCCO single crystals



The channels (weak pinning) should not contain any macroscopic defects. \Rightarrow Necessary to select macroscopic defect-free single crystals.

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Sample preparation

Realization of channel structure through irradiation (GANIL)

Selective irradiation through nickel masks

Thickness of a nickel mask is 6 \sim 10 $\mu m.$ 4 to 5 masks were superposed to block the Pb⁵⁶⁺ ion beam of 1 GeV.

Definition of matching field B_d

Sample preparation

Realization of channel structure through irradiation (GANIL)



selective irradiation

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Definition of matching field B_{ϕ}

Plasma etching

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Photolithography



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bulk pinning vs. surface pinning

Verification: bulk or surface properties?

- Mapping of critical current.
- Current path imaging.
- Transport measurements.

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bulk pinning vs. surface pinning

Experimental results: MOI



Mapping of critical current

Field modulated MOI acquired at T = 80.5 K with field modulation of 0.5 Oe, base field = 25 Oe, on BSCCO crystal "*iv*" (clean 20 μm wide channels).

Current path imaging

Current modulated differential image acquired at T = 68 K, $H_{//c}$ = 100 Oe, with I = +30 mA, -30 mA, on BSCCO crystal "24-4" (channels + low density of columnar defects (B_{ϕ} = 10 G) in the channels).

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bulk pinning vs. surface pinning

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Experimental results: transport measurements



Bulk flow.Signature of shear flow.

bulk pinning vs. surface pinning

Experimental results: transport measurements



Arrhenius plot of the voltage vs temperature for selected magnetic fields. The measuring current density was 1×10^6 A/m^2 . $\Box:10$ mT, $\bigcirc:20$ mT, $\bigtriangleup:30$ mT, $\bigtriangledown:40$ mT, $\circlearrowright:40$ mT, $\diamondsuit:40$ mT, $\lhd:40$ mT, a:40 mT, a=40 mT, a:40 mT, a:40 mT, a=40 m,



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bulk pinning vs. surface pinning

Summary: bulk pinning vs. surface pinning

Experimental facts

- Field modulated differential magneto-optical imaging $\Rightarrow j_{c, walls} > j_{surface}$.
- Current path imaging \Rightarrow current flows through the irradiated structure.
- Transport measurements: no nonlinear resistance ⇒ no surface barrier effect in liquid vortex state.

Therefore we probe the bulk.

bulk pinning vs. surface pinning

Summary: bulk pinning vs. surface pinning

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Characteristic fields and temperatures



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Comparison with 2D melting model

D = 2: Nelson-Halperin model



scaling law of resistivity

 $\rho(T) \approx C_1 \exp[-2C_2(\frac{T_m}{T-T_m})^{0.37}],$ where $C_1 \sim \rho_{flux-flow}, C_2 \sim 1$, and T_m is the melting (freezing) temperature.

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Remarkably, R(T) of our 3D superconductor is well fitted with 2D scaling law ...

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I-V characterization

2D Nelson-Halperin melting property

Power law: $V = I^a$, where the exponent *a* has a universal jump from 1 to 3 at $T = T_m$ (characteristic of 2D melting).

This jump is observed!

Measurements performed on a $Bi_2Sr_2CaCu_2O_8$ single crystal, containing clean 20 μm wide channels.

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- Current flows only at the top layer. (B. Khaykovich et al., Phys. Rev. B 61, R9261 (2000))
- A dimension cross-over takes place nearly simultaneously with the liquid (2D) solid (3D) transition.



Suggestion

Multi-terminal transport measurements with electrical contacts on both the top and bottom surfaces.



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Comparison with 3D Bose-glass model

D = 3 with columnar defects: Bose-glass model

Marchetti and Nelson's proposal

Introduce a low density of columnar defects in the channels. A Bose liquid state should be realized in the channels.

Prediction

- Vortex liquid to Bose-glass transition at T_{BG}.
- Near T_{BG}, ρ(T) ~ L²|T − T_{BG}|^{v⊥Z} for channel confined vortices.
- v_⊥ is the static critical exponent, z is the dynamic critical exponent. Simulations: v_⊥ ≈ 1,z ≈ 4.6.

Reference: non-confined Bose-liquid

Near
$$T_{BG}$$
, $\rho(T) \sim |T - T_{BG}|^{v_{\perp}(z-2)}$

Results ○○○○●●

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Comparison with 3D Bose-glass model

Experimental data vs. 3D Bose-glass model



BSCCO "24-4", containing low density columnar defects (B_{ϕ} = 10 G) in the 20 μm wide channels. s = 1.9



BSCCO "10G", uniformly irradiated with a dose of B_{ϕ} = 10 G. 1.2 < s < 1.8 we find: s = 0.8 + 0.0032*H*.

Discussions

Summary

Comparison of different types of confinement



Degree of confinement comparison:

20 μ *m* wide channels + B_{ϕ} = 10 G

 $\overline{\approx B_{\phi}}$ = 10 G > 20 μm wide clean channels > pristine.

Confinement realized in a uniformly irradiated sample



Magnetic decoration with $B = 8B_{\phi}, B_{\phi} = 10$ G. From: M. Menghini et al., PRL **90**, 087004 (2003)

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- Bulk vortex properties have been successfully probed.
- Both of the 2D and 3D models fit with the experimental resistance data approaching zero-resistance. Why?
 - $\rho_{\rm c} \rightarrow 0.$
 - Surface barrier contribution when it becomes effective.
 - Defects in 3D vortex lattice yield similar contribution to ρ(T) as defects in 2D vortex lattice.
 - Defects in vortex lattice in layered BSCCO resemble 2D defects (i.e., pancake vortices).
- Field modulated differential magneto-optical imaging can serve as a tool for estimating transport current flow distribution prior to the transport measurements.
- Outlook
 - Varying channel width: size effect.
 - Establishing electrical contacts on both the top and bottom surfaces: *c*-axis correlation.
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Acknowledgment

Kees van der Beek Marcin Konczykowski Rozenn Bernard Javier Briatico Panayotis Spathis Tatiana Taurines

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Thank you for your attention!

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