Experimental Condensed Matter Physics: Superconductivity and Magnetism

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This is a “hands-on,” collaborative research program directed toward a physical understanding of materials, particularly their interaction with magnetic fields. **Superconductivity** and **ferromagnetism** (also ferri- and anti-ferromagnetism) are cooperative phenomena that are strongly affected by an external magnetic field.

Research topics range from exotic features of superconductors to technological development of HTSC-based “coated conductors,” to nanomagnetism of lunar dust and bacteria by-products.

Funding: ~100 k$/year at UTK.

Seminar on UTK research programs, 7 November 2007
Present Group & collaborations

Anota IJADUOLA (Postdoc)
Valentina KUZNETSOVA (coadvise w/ Prof Barzykin)
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COLLABORATIONS at UTK
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Yifei ZHANG (MS&E)
Larry TAYLOR, Yang LIU (Geological Sciences)
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COLLABORATIONS at ORNL
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FURTHER COLLABORATIONS
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Generic phase diagram for a Type II superconductor

- Magnetic flux enters as vortices with $\Phi_0 = h/2e$
- Radius of $\Phi_0$ currents $\leftrightarrow H_c^1$
- Radius of $\Phi_0$ core $\leftrightarrow H_c^2$
- Vortex matter in the mixed state may organize into a crystal, a glassy state, or melt into a liquid.

\[ H_{c1} = \frac{\Phi_0}{4\pi \lambda^2} \ln(\kappa) \]
\[ H_{c2} = \frac{\Phi_0}{2\pi \xi^2} \]

Magnetization vs field
In mixed state, microscopic currents generate vortices

Qiang Du,
http://www.math.psu.edu/
Circulating current density $j$ creates & supports local field $b$. (These sketches are all for a bulk superconductor. In a thin film, $b$ and $j$ change algebraically over a “screening length” $\Lambda=\lambda^2/d$.)
Images of Vortex Lattice and Arrays in Superconductors

STM image of Vortex lattice, 1989

Scanning Tunnel Microscopy
NbSe$_2$, 1T, 1.8K

H. F. Hess et al.
Bell Labs
Vortex “pinning” - Create tailored ‘defects’ to match vortex geometry and number

Create strong potential wells (‘pins’) for vortices with latent tracks via ion irradiation.

- Linear geometry matches vortex geometry
- Track diameter $\approx$ core size $\xi$
- Area density of tracks $B_\phi \approx$ vortex density $B$
- “Columnar defects”

TEM image of columnar defects in YBaCuO, created by irradiation with 1 GeV Au-ions. (R. Wheeler)
Critical current density $J$ for YBa$_2$Cu$_3$O$_7$ with columnar defects

The energy functional for an isolated vortex in a columnar defect has the same form as a boson in a cylindrical “square well.”

Quantities map as:

- Mass $m$ $\Rightarrow$ vortex line tension $\mu$
- Planck’s constant $h$ $\Rightarrow$ temperature $T$

Well depth

Zero point energy:

$E_0 = \frac{h^2}{8mL^2} \Rightarrow E_0 \sim T^2/\mu L^2$

So quantum mechanics “hurts”: increasing temperature $T$ increases the zero point energy, causing a vortex to depin. Hence $J_c(T)$ decreases.
Quantum controlled growth of Pb films: voids trap vortices and give a high $J_c$; with mesas, a vortex has only to avoid them to move => low $J_c$

$T = 2 \text{ K}$

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collaboration with M.M. Özer, Yu Jia, Zhenyu Zhang, JRT, and H. H. Weitering
**Strong Vortex Pinning by Voids**

Scale of vortex line energy per unit length:
\[ \varepsilon_0 = \left( \frac{\Phi_0}{4\pi\lambda} \right)^2 \]

Vortex pinning energy:
\[ U_0 = \varepsilon_0 \Delta d \]

Maximum vortex pinning force:
\[ f_{pin} = -\nabla U_0 \approx \frac{\varepsilon_0 \Delta d}{\xi} \]

and balancing “Lorentz” force gives
\[ f_{pin} = \xi^{-1} J_c \Phi_0 d \]

yielding estimated current density
\[ J_c \approx J_{DEPAIR} \left( \frac{\Delta d}{d} \right) \approx 4 \text{ MA/cm}^2 \]

Experimentally ($T = 2$ K):
\[ J_c = [2.0 \text{ (dc)} - 2.8 \text{ (ac)}] \text{ MA/cm}^2. \]
Thank you
for your attention and interest!