The Competitive Landscape of High-Tc Superconductivity

Jenny Hoffman

Experiments:
Magdalena Huefner
Jeehoon Kim
Liz Main
Tess Williams
Yi Yin
Martin Zech
Ilija Zeljkovic
Harvard Physics

Mike Boyer
Kamalesh Chatterjee
Doug Wise
Eric Hudson
MIT Physics

Samples:
Takeshi Kondo
T. Takeuchi
Hiroshi Ikuta
Nagoya University

XiangFeng Wang
Gang Wu
Xianhui Chen
USTC

Genda Gu
Brookhaven

Paul Canfield
Ames Lab, Iowa

Thanks to:
Hoffman Lab Local Probes

Scanning Tunneling Microscope

Force Microscope

Ultra-high vacuum STM

Bi-2201
122 iron pnictide
topological insulator
NbSe$_2$
metal-insulator transition in VO$_2$
1111 iron pnictide
Bi-2212
Outline

Superconductors: 100 Year History

Pseudogap in cuprates:
- Competing or collaborating?
- Inter-unit-cell order: checkerboards
- Intra-unit-cell order: nematicity, inversion symmetry breaking

Vortex pinning in cuprates & pnictides:
- STM imaging of Ba-122, 3-dim isotropy
- MFM imaging of NdFeAsO, in-plane anisotropy
Superconductors: 100 Year History

Pseudogap in cuprates:
- Competing or collaborating?
- Inter-unit-cell order: checkerboards
- Intra-unit-cell order: nematicity, inversion symmetry breaking

Vortex pinning in cuprates & pnictides:
- STM imaging of Ba-122, 3-dim isotropy
- MFM imaging of NdFeAsO, in-plane anisotropy
Heike Kamerlingh Onnes (right) and Gerrit Flim, his chief technician, at the helium liquefier in Kamerlingh Onnes’s Leiden laboratory, circa 1911.

Physics Today, Sept 2010
2 Properties of Superconductors

1. Vanishing of electrical resistivity (by Cooper pairing)

2. Expulsion of magnetic field (by shielding currents)

Kamerlingh-Onnes, 1911

Meissner, 1933
## 2 Types of Superconductors

<table>
<thead>
<tr>
<th>Material</th>
<th>$T_c$ (Kelvin)</th>
<th>$H_c$ (Tesla)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mercury</td>
<td>4.15</td>
<td>0.0411</td>
</tr>
<tr>
<td>Lead</td>
<td>7.2</td>
<td>0.0803</td>
</tr>
<tr>
<td>Aluminum</td>
<td>1.19</td>
<td>0.0099</td>
</tr>
<tr>
<td>Vanadium</td>
<td>5.3</td>
<td>0.1370</td>
</tr>
<tr>
<td>Niobium</td>
<td>9.2</td>
<td>0.1944</td>
</tr>
<tr>
<td>NbTi</td>
<td>10</td>
<td>15</td>
</tr>
<tr>
<td>NbSn$_3$</td>
<td>20</td>
<td>30</td>
</tr>
</tbody>
</table>

Type I: Meissner

Type II: Vortices

→ Type II Superconductors are generally more useful
Vortex Challenges

Normal electrons in vortex core cause dissipation when moved.

Apply current $I$: Cooper pairs flow without dissipation.

→ need some mechanism to *pin* vortices in place.

Center of vortex: superconductivity is destroyed → costs energy!

so introduce defects where superconductivity is already compromised → avoid paying energy cost twice!

Applications of Superconductors

Magnetic Resonance Imaging (MRI)

Large Hadron Collider (LHC) particle physics research: need large magnets to accelerate protons in 4.3-km ring
A Long History of Superconductivity

1911 – Kamerlingh Onnes – first superconductivity in Hg
1933 – Meissner – superconductors screen B-field
1952 – Abrikosov – predicted vortices
1957 – Bardeen, Cooper & Schriefer – theoretical understanding
1962 – Josephson – field-dependent tunneling (SQUIDS)

Vortex pinning problem largely solved...
but still not so many practical applications because T requirements so severe…
History of Superconducting $T_c$

![Graph showing the history of superconducting $T_c$ with the years of discovery for various superconductors: Hg, Pb, Nb, NbN, V$_3$Si, Nb$_3$Sn, HgBaCaCuO, TlSrBaCuO, BiCaSrCu$_2$O$_9$, YBa$_2$Cu$_3$O$_7$, LaBaCuO$_4$, and Nb$_3$Ge. The graph plots temperature [K] against the year of discovery.]
A Long History of Superconductivity

1911 – Kamerlingh Onnes – first superconductivity in Hg

1933 – Meissner – superconductors screen B-field

1952 – Abrikosov – predicted vortices

1957 – Bardeen, Cooper & Schriefer – theoretical understanding

1962 – Josephson – field-dependent tunneling (SQUIDS)

Vortex pinning problem largely solved…
but still not so many practical applications because T requirements so severe…

1986 – Bednorz & Mueller – high-Tc superconductors

→ 1913 Nobel Prize
→ 2003 Nobel Prize
→ 1972 Nobel Prize
→ 1973 Nobel Prize
→ 1987 Nobel Prize
Applications of Cuprate Superconductors

Maglev Trains:
Southwest Jiaotong University, China

American Superconductor:
more efficient motors & generators
e.g. this 5 MegaWatt motor is
~30% weight, 50% size
of conventional motor
→ great for ships, airplanes!

IEEE Transactions on Applied Superconductivity
19, 2142 (2009)
Applications of Cuprate Superconductors

American Superconductor: cooled cables for power transmission

Filters in cell phone relay stations
→ make better use of bandwidth
→ put relay stations farther apart
→ reduce signal strength (safer cell phones)
Projected World Markets

Superconductors:

- Medical
- Industrial
- Transportation
- Energy
- Electronics

Semiconductors:

(Conectus, 2004)

(Sakurai, 1999)
A Long History of Superconductivity

1911 – Kamerlingh Onnes – first superconductivity in Hg  ➔ 1913 Nobel Prize
1933 – Meissner – superconductors screen B-field
1952 – Abrikosov – predicted vortices  ➔ 2003 Nobel Prize
1957 – Bardeen, Cooper & Schriefer – theoretical understanding  ➔ 1972 Nobel Prize

Vortex pinning problem largely solved…
but still not so many practical applications because T requirements so severe…

1986 – Bednorz & Mueller – high-Tc superconductors  ➔ 1987 Nobel Prize

Still not so many practical applications…
severe vortex pinning problems in cuprates…
T requirements still non-trivial…
Material Considerations

**Problems:**
- Ag matrix is expensive
- Crystal grains poorly aligned
- Poor conduction across grain boundaries
- Anisotropy very high (~50!)

**Advantages:**
- Cheaper materials
- Tapes are aligned on 2 axes → cuts down on grain boundaries
- Anisotropy is only ~7
- Non-vacuum manufacture processes

**Materials:**
- Bi$_2$Sr$_2$CaCu$_2$O$_{8+d}$/Ag wires
- YBa$_2$Cu$_3$O$_{7-d}$ tapes

**References:**
- Scanlan, IEEE 92, 1639 (2004)
Trouble With Vortices

Conventional Superconductors

Cuprate Superconductors

Larbalestier, Nature 414, 368 (2001)
Conventional Superconductors

- normal state is metallic
- materials are ductile, easy to make wires
- Fermi liquid ground state is a well-understood starting point for the theory of superconductivity

Cuprate Superconductors

- “normal” state is insulating
- how can that be?
- how can we hope to understand superconductivity, if we don’t even understand its precursor state?
Cuprate Phase Diagram

3-dim cuprate phase diagram

antiferromagnetic insulator

d-wave superconductor

energy (meV)
density of states

doped Mott insulator becomes metal
Cuprate Phase Diagram

“Here be dragons”

“strange metal”

doped Mott insulator becomes metal

antiferromagn insulator

d-wave superconductor

3-dim cuprate phase diagram

antiferromagnetic insulator

x (doping)
A Long History of Superconductivity

1911 – Kamerlingh Onnes – first superconductivity in Hg
1933 – Meissner – superconductors screen B-field
1952 – Abrikosov – predicted vortices
1957 – Bardeen, Cooper & Schriefer – theoretical understanding
1962 – Josephson – field-dependent tunneling (SQUIDS)

Vortex pinning problem largely solved…
but still not so many practical applications because T requirements so severe…

1986 – Bednorz & Mueller – high-\(T_c\) superconductors

Still not so many practical applications…
severe vortex pinning problems in cuprates…
T requirements still non-trivial…

Today’s frontiers:
1. discover higher-\(T_c\) materials → need to understand the ones we’ve got
2. improve vortex pinning in high-\(T_c\) materials
Outline

Superconductors: 100 Year History

Pseudogap in cuprates:
- Competing or collaborating?
- Inter-unit-cell order: checkerboards
- Intra-unit-cell order: nematicity, inversion symmetry breaking

Vortex pinning in cuprates & pnic tid es:
- STM imaging of Ba-122, 3-dim isotropy
- MFM imaging of NdFeAsO, in-plane anisotropy
Ordinarily:
If lowering T opens a gap, this means some symmetry has been broken. → Look for broken symmetry!

Problem:
Cuprates are disordered… → no obvious long-range symmetry breaking was initially seen experimentally

Theorists propose: hidden broken symmetries!
Fluctuating stripes play to role of the “nematogens” which allows for the formation of various “electronic liquid crystalline phases” in the pseudo-gap regime.

Local stripe order may enhance pairing, but stripe order certainly suppresses superfluid stiffness.

**Nematic:**
breaks long-range rotation

**Smectic:**
breaks long-range rotation & translation

Underdoped cuprates have a hitherto undetected broken symmetry phase which does not break translation symmetry.

The non-Fermi liquid “normal” state is the **quantum critical regime**, in which order parameter fluctuations strongly scatter the quasiparticles.

The critical fluctuations “mediate” d-wave pairing.

**Breaks time-reversal and inversion but not the produce of TI.**
Outline

Superconductors: 100 Year History

Pseudogap in cuprates:
- Competing or collaborating?
- Inter-unit-cell order: checkerboards
- Intra-unit-cell order: nematicity, inversion symmetry breaking

Vortex pinning in cuprates & pnictides:
- STM imaging of Ba-122, 3-dim isotropy
- MFM imaging of NdFeAsO, in-plane anisotropy
Relationship Between PG and SC?

Does SC arise out of PG? Or do the two compete?

doped Mott insulator becomes metal

antiferromagnetic insulator

d-wave superconductor


d-wave superconductor

energy (meV)
density of states

above T_c

low T
Crash Course in Solid State Physics

Brought to you by:
Me: “how do I explain a Brillouin zone?”

4-year-old who is stuck with 2 physicists for parents: “Mommy, it’s a box that electrons live in!”
Band Theory

Single atom:

- 3s
- 2p
- 2s
- 1s

Crystal:

Add momentum information:

Brillouin zone edge:

highest unique wavevector $k$ (larger $k$'s aren't sampled by the atoms so they are aliased back to smaller $k$'s)

$\lambda_{\text{min}} \leftrightarrow k_{\text{max}}$
**Band Theory: Metal**

---

**Single atom:**
- 3s
- 2p
- 2s
- 1s

**Crystal:**

---

**Add momentum information:**

- Brillouin zone edge: highest unique wavevector $k$ (larger $k$’s aren’t sampled by the atoms so they are aliased back to smaller $k$’s)

- $\lambda_{\text{min}} \leftrightarrow k_{\text{max}}$
Add e-e correlations: Mott Insulator

Single atom:

- 3s
- 2p
- 2s
- 1s

Crystal:

Add momentum information:

$E$ vs $k$

$U$
Mott Transition

localized

\[\xrightarrow{\text{delocalized}}\]

further delocalized

\[\xrightarrow{\text{delocalized}}\]
What is a Brillouin zone?

Contours represent vertical height:
What is a Brillouin zone?

Topographic map: contours represent physical height

Brillouin zone: contours represent electron energy

Real space: $y$ $x$

Momentum space: $k_y$ $k_x$

Filled states (electrons)

Empty states (holes)

Contours from -100meV to +100meV
Cuprate Phase Diagram

- Antiferromagnetic insulator
- D-wave superconductor
- Pseudogap
- Doped Mott insulator becomes metal


energy (meV) density of states
energy (meV) density of states
Cuprate Brillouin Zone: “Normal” state

CCE (E): The location in k-space of states with energy E.

Fermi Surface

In a superconductor: e-e pairs form on FS.

Parameterization:
M. Norman

Based on data:
Ding et al.,
Cuprate Brillouin Zone: Gap vs. angle

Contours from -100 meV to +100 meV

Ding et al., PRL 54, 9678 (1996)
Shen et al., PRL 70, 1553 (1993)
Ding et al., PRB 54, 9678 (1996)
Mesot et al., PRL 83, 840 (1999)
STM and ARPES both show competition between superconductivity (wins in nodal region) & pseudogap (wins in antinodal region).

STM
Pushp, Science 324, 1689 (2009)

ARPES
Kondo, Nature 457, 296 (2009)
→ We want to know what the PG is (i.e. what symmetries it breaks) so we can control it & mitigate the competition!!

No obvious long-range order → use real space probe → STM
Introduction to STM

Tip
Sample

Tip
Sample

E

GΩ

Sample LDOS under tip

Sample

TIP DOS

E_F (sample)

E_F (tip)

vacuum
Introduction to STM

$$I(V) = \int_{E_F}^{E_F + eV} \text{LDOS}(E) dE$$

Sample LDOS under tip

Vacuum

TIP DOS

Sample

Tip

GΩ

V
Introduction to STM

Sample

Tip

\[ \frac{dI}{dV} \propto LDOS(eV) \]

modulate by dV

E_F (tip)

Sample LDOS under tip

TIP DOS

E_F (sample)
Types of STM Measurements

Local Density of States \( (x, y, E) \)

\[ \int \frac{dI}{dV} \]

Constant current mode:

\[ \int_{0}^{2 \, \text{Å}} \frac{dI}{dV} \text{ Spectrum} \]

\[ \text{DOS} \]

\[ \text{energy} \]

\[ \text{d}I/dV \text{ Map} \]

\[ \text{Topography} \]
Structure of $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$

- $a \approx b = 5.4 \text{ Å}$
- $c = 30.7 \text{ Å}$
- $T_c \sim 90 \text{ K}$

Cleave Here Reveals BiO Surface

Cleave Here Reveals BiO Surface
$\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$

$T = 4.2\,\text{K}, B = 0\,\text{T}$
$100\,\text{pA}, -100\,\text{mV}$

560 Å
$\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$

$T = 4.2$K, $B = 0$T
100pA, -100mV
280 Å
$\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$

$T = 4.2K, B = 0T$

$100\text{pA}, -100\text{mV}$

$140\text{Å}$
$\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$

$T = 4.2\, \text{K}$, $B = 0\, \text{T}$

$100\, \text{pA}$, $-100\, \text{mV}$

$70\, \text{Å}$
$\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$

Each bright spot is a Bi atom.

Size & orientation of CuO$_2$ unit cell (~5 Å below surface).

$T = 4.2\text{K}, B = 0\text{T}$

100pA, -100mV
Outline

Superconductors: 100 Year History

Pseudogap in cuprates:
- Competing or collaborating?
- Inter-unit-cell order: smectics, checkerboards
- Intra-unit-cell order: nematicity, inversion symmetry breaking

Vortex pinning in cuprates & pnictides:
- STM imaging of Ba-122, 3-dim isotropy
- MFM imaging of NdFeAsO, in-plane anisotropy
**Inter-unit-cell ordering: “checkers”**

3-dim cuprate phase diagram

- Antiferromagnetic insulator
- D-wave superconductor
- "Nematic" and "Smectic"

- Electronic cluster glass

- "Nematic" and "Smectic"

Parker, Nature (2010)


**“Fluctuating Stripes”**
“Checkers”: CDW from Nesting

holes pocket: expands on increased doping

→ This state breaks translation symmetry but not rotation symmetry!

Pseudogap decreases with doping

- hole pocket expands with doping
- nesting wavevector decreases with doping
Gapmap: map of $\Delta$ as a function of location

Differential Conductance (nS) vs. Sample Bias (mV)
Gapmap: map of $\Delta$ as a function of location

- $\Delta = 38.5$ meV
- $\Delta = 36.7$ meV
- $\Delta = 35.3$ meV

McElroy, PRL (2005)

~ 600 Å
Look at just range of gap sizes:
e.g. Mask range: 37 to 42 meV
Gap-Based Checkerboard Evolution

Bi-2212, slightly OD: FFT of 50 nm, 4 K, E=30 mV

$\Delta_{\text{PG}} (\text{meV})$

$<\Delta> = 42 \text{ mV}$
Gap-Based Checkerboard Evolution

Bi-2212, slightly OD: FFT of 50 nm, 4 K, E=30 mV

$\langle \Delta \rangle = 55 \text{ mV}$

$\sigma_\Delta = 6 \text{ mV}$
Gap-Based Checkerboard Evolution

Bi-2212, slightly OD: FFT of 50 nm, 4 K, E=30 mV

(0,2π)

(2π,0)

<Δ>=45 mV

σ_Δ = 1.7 mV

Δ_PG (meV)

Number of occurrences
Gap-Based Checkerboard Evolution

Bi-2212, slightly OD: FFT of 50 nm, 4 K, E=30 mV

\( \langle \Delta \rangle = 40 \text{ mV} \)

\( \sigma_\Delta = 1.3 \text{ mV} \)
Gap-Based Checkerboard Evolution

Bi-2212, slightly OD: FFT of 50 nm, 4 K, E=30 mV

<Δ>=34 mV
σ_Δ = 2.4 mV
Gap-Based Checkerboard Evolution

**Our Data:**

Bi-2212, from slightly OD sample, $T=4K$

**Previous Data:**

**Closer look: stripes or checkers?**

<table>
<thead>
<tr>
<th>Stripes Type</th>
<th>Disorder</th>
</tr>
</thead>
<tbody>
<tr>
<td>Static stripes. Weak disorder</td>
<td>Static CB. Weak disorder</td>
</tr>
<tr>
<td>Static stripes. Stronger disorder</td>
<td>Static CB. Stronger disorder</td>
</tr>
<tr>
<td>Pinned fluctuating stripes. Weak disorder</td>
<td>Pinned fluctuating CB. Weak disorder</td>
</tr>
</tbody>
</table>

Robertson, Kivelson, PRB 74, 134507 (2006)
Charge modulation:

\[ \rho(r) = \bar{\rho} + [\varphi_1(r)e^{iQ_{x}x} + \varphi_2(r)e^{iQ_{y}y} + \text{c.c.}] \]

Hamiltonian:

\[ H_{\text{eff}} = \frac{\kappa_L}{2} \left[ |\partial_x \varphi_1|^2 + |\partial_y \varphi_2|^2 \right] + \frac{\kappa_T}{2} \left[ |\partial_y \varphi_1|^2 + |\partial_x \varphi_2|^2 \right] + \frac{\alpha}{2} \left[ |\varphi_1|^2 + |\varphi_2|^2 \right] + \frac{u}{4} \left[ |\varphi_1|^2 + |\varphi_2|^2 \right]^2 + \gamma |\varphi_1|^2 |\varphi_2|^2 \]

Correlation lengths:

\[ \xi_{\text{CDW}}^2 = \frac{\int dr |A|^2}{\int dr |A|^2} \]

\[ \xi_{\text{orient}}^2 = \frac{\int dr \left[ |A_1|^2 - |A_2|^2 \right]^2}{\int dr \left[ |A_1|^2 - |A_2|^2 \right]^2} \]

\( \xi_{\text{CDW}} \) and \( \xi_{\text{orient}} \) = complex values of charge modulation in x, y directions

Robertson, Kivelson, PRB 74, 134507 (2006)
Stripe domains?

unpublished data
Inter-unit-cell checkerboard: Conclusions

1. Checkerboard seen for 10 years → many names

   - **Checkerboard**
   - **Charge Density Wave**
   - **Electronic Cluster Glass**
   - **“Smectic”**
   - **“Fluctuating Stripes”**

   *Hoffman, Science (2002)*
   *Wise, Nat Phys (2008)*
   *Kohsaka, Nature (2008)*
   *Lawler, Nature (2010)*
   *Parker, Nature (2010)*

2. Checkerboard wavelength correlates with antinodal nesting wavevector in Brillouin zone

3. Checkerboard=pseudogap, competes with superconductivity

Next step: is it really a checkerboard? or small, disordered domains of stripes?
Superconductors: 100 Year History

Pseudogap in cuprates:
• Competing or collaborating?
• Inter-unit-cell order: checkerboards
• Intra-unit-cell order: nematicity, inversion symmetry breaking

Vortex pinning in cuprates & pnictides:
• STM imaging of Ba-122, 3-dim isotropy
• MFM imaging of NdFeAsO, in-plane anisotropy
Intra-unit-cell ordering: nematicity? inversion?

(“nematic” = fluid state which breaks rotation symmetry, but not translation)

Goals:
1. detect “nematic” orbital ordering = difference between 2 inequivalent O sites
2. detect “inversion symmetry breaking” at Cu sites

Implementation:
1. nematic: is there difference between x & y real parts of FT?
2. inversion: is there imaginary part of FT?


Lawler, Davis, Kim invented drift correction algorithm to line up atoms onto perfect grid!
Lawler’s “Nematic”

Lawler:
1. use the topography to get the drift-correction field
2. apply the same drift-correction field to the density of states at the pseudogap energy
3. compare the single-pixel Re(Qx) and Re(Qy) to look for nematicity

“Long range” order in 40nm sq

Order is strongest at Pseudogap energy

Our data: Bi-2201 without supermodulation

Topography:
30 nm x 30 nm

Optimally doped Bi-2201
(Tc = 35K)

Pb-doped to remove supermodulation

Hudson/Hoffman lab, combined Bi-2201 datasets
Our data: Bi-2201 without supermodulation

Density of states at $E=30$ meV: 30 nm x 30 nm

Optimally doped Bi-2201 ($T_c = 35K$)
Pb-doped to remove supermodulation

Hudson/Hoffman lab, combined Bi-2201 datasets
Imaginary Complications

Optimally doped
Bi-2201
(Tc = 35K)

Re(Qx) - Re(Qy) = Lawler’s nematic
Im(Qx) - Im(Qy)

Δ_{PG} \sim 30 \text{ meV}

Hudson/Hoffman lab, combined Bi-2201 datasets
<table>
<thead>
<tr>
<th>Structural</th>
<th>Electronic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bi-2212</td>
<td>Bi-2201, Pb-doped</td>
</tr>
<tr>
<td>Bi-2201, Pb-doped</td>
<td>another Bi-2201, Pb-doped</td>
</tr>
</tbody>
</table>

Images of Bi-2212, Bi-2201, and another Bi-2201, Pb-doped.
Raw data

(Bi-2201, Tc=32K, slightly underdoped)

Bragg peaks are blurred → need to apply Lawler algorithm to drift-correct!

66×66 nm²
Drift-corrected data

(Bi-2201, Tc=32K, slightly underdoped)

center pix > 5x brighter than nearest neighbors
Make Average Unit Cell

- Pixel grid
  - exact tip location when data acquired

Bi atom

- Make a new grid, one unit cell, but with more pixels than in raw data.
- Center Bi in center of this unit cell.
- Build up a histogram of weight at each sub-unit-cell-resolved location.

Note: data acquisition only slightly better than Nyquist frequency for atoms!

Perfect registry allows sub-unit-cell resolution!
Make Average Unit Cell
(Bi-2201, Tc=32K, slightly underdoped)

make average unit cell

tile 4x4

66x66 nm²
Make Average Unit Cell

(Bi-2201, Tc=32K, slightly underdoped)

make average unit cell

fit to make sure Bi is at center, where we think it should be
Make Average Supercell: 2x2

(Bi-2201, Tc=32K, slightly underdoped)

shift by ~1% of unit cell
Make Average Supercell: 4x2

(Bi-2201, Tc=32K, slightly underdoped)
Make Average Supercell: 4x4

(Bi-2201, Tc=32K, slightly underdoped)

16 inequivalent sites:
average displacement: 1.1%
standard deviation: 0.36%
(error bar ~1/3 of effect → inconsistent with zero)
Crystal Structure

\[ \text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8 \]

- BiO
- SrO
- CuO\(_2\)
- Ca
- SrO
- CuO\(_2\)
- BiO
- SrO
- CuO\(_2\)
- Ca
- BiO
- SrO
- CuO\(_2\)
- BiO

\[ \text{tetragonal BZ} \]
\[ \text{orthorhombic BZ} \]
Apply avg unit cell methods to many samples

Zeljkovic, arxiv:1104.4342
Bi-2201 throughout the SC dome

Figure a: 3D graph showing the relationship between temperature (T), doping, and magnetic field (B). The graph includes data points indicating the shift (% Ortho Unit Cell) for different TC values.

Figure b: Graph showing the shift (% Ortho Unit Cell) as a function of magnetic field (T) at fixed doping levels.

Figure c: Graph showing the shift (% Ortho Unit Cell) as a function of temperature (K) at fixed doping levels.

Figure d: Graph showing the shift (% Ortho Unit Cell) as a function of doping (p from TC) at fixed temperatures.
8 different Bi-2212 samples

\( Q_{SM} \equiv \text{crystalline } b \text{ axis} \)

10 samples: ortho distortion along \( a \) axis

mirror plane always chooses this axis
### Historical: Structure from Scattering

<table>
<thead>
<tr>
<th>Material</th>
<th>Pb?</th>
<th>Technique</th>
<th>Bi distortion</th>
<th>Cu distortion</th>
<th>Ref</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bi-2223</td>
<td>no</td>
<td>XRD</td>
<td>2.22% (b axis)</td>
<td>-0.01% (b axis)</td>
<td>Subramanian, Science (1988)</td>
</tr>
<tr>
<td>Bi-2201</td>
<td>no</td>
<td>XRD</td>
<td>2.58% (b axis)</td>
<td>none</td>
<td>Torardi, PRB (1998)</td>
</tr>
<tr>
<td>Bi-2212</td>
<td>no</td>
<td>neutrons</td>
<td>2.55% (a axis)</td>
<td>-0.07% (a axis)</td>
<td>Miles, Physica C (1998)</td>
</tr>
<tr>
<td>Bi-2201</td>
<td>yes</td>
<td>XRD</td>
<td>1.82% (a axis) 6.34% (b axis)</td>
<td>none</td>
<td>Ito, PRB (1998)</td>
</tr>
<tr>
<td>Bi-2212</td>
<td>yes</td>
<td>XRD</td>
<td>1% (a axis) 1.65% (b axis)</td>
<td>2.57% (a axis) -0.02% (b axis)</td>
<td>Calestani, Physica C (1998)</td>
</tr>
<tr>
<td>Bi-2212</td>
<td>yes</td>
<td>XRD</td>
<td>1.1% (a axis) 1.53% (b axis)</td>
<td>0.08% (b axis)</td>
<td>Gladyshevskii, PBR (2004)</td>
</tr>
<tr>
<td>Bi-2201</td>
<td>yes and no</td>
<td>LEED, ARPES one axis only</td>
<td>can’t determine</td>
<td>Mans, PRL (2006)</td>
<td></td>
</tr>
</tbody>
</table>
STM adds: \textit{LOCAL} symmetry determination

Bi-2201: Tc=25K, UD

local mirror planes!
In the absence of supermodulation, there can be twin boundaries → leads to the appearance of shifts along 2 axes

<table>
<thead>
<tr>
<th>Material</th>
<th>Pb?</th>
<th>Technique</th>
<th>Bi distortion</th>
<th>Cu distortion</th>
<th>Ref</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bi-2223</td>
<td>no</td>
<td>XRD</td>
<td>2.22% (b axis)</td>
<td>-0.01% (b axis)</td>
<td>Subramanian, Science (1988)</td>
</tr>
<tr>
<td>Bi-2201</td>
<td>no</td>
<td>XRD</td>
<td>2.58% (b axis)</td>
<td>none</td>
<td>Torardi, PRB (1998)</td>
</tr>
<tr>
<td>Bi-2212</td>
<td>no</td>
<td>neutrons</td>
<td>2.55% (a axis)</td>
<td>-0.07% (a axis)</td>
<td>Miles, Physica C (1998)</td>
</tr>
<tr>
<td>Bi-2201</td>
<td>yes</td>
<td>XRD</td>
<td>1.82% (a axis) 6.34% (b axis)</td>
<td>none</td>
<td>Ito, PRB (1998)</td>
</tr>
<tr>
<td>Bi-2212</td>
<td>yes</td>
<td>XRD</td>
<td>1% (a axis) 1.65% (b axis)</td>
<td>2.57% (a axis) -0.02% (b axis)</td>
<td>Calestani, Physica C (1998)</td>
</tr>
<tr>
<td>Bi-2212</td>
<td>yes</td>
<td>XRD</td>
<td>1.1% (a axis) 1.53% (b axis)</td>
<td>0.08% (b axis)</td>
<td>Gladyshevskii, PBR (2004)</td>
</tr>
<tr>
<td>Bi-2201</td>
<td>yes and no</td>
<td>LEED, ARPES</td>
<td>one axis only</td>
<td>can’t determine</td>
<td>Mans, PRL (2006)</td>
</tr>
</tbody>
</table>
Intra-unit-cell structure: Conclusions

1. structural distortion in BiO plane breaks inversion symmetry at the Bi site, but preserves mirror plane

2. mirror plane is always aligned with supermodulation

3. can image the local mirror plane

4. resolve long discrepancies in the bulk scattering literature:
   - supermodulated samples → no ortho twinning;
   - Pb-doped samples → can have ortho twinning

5. orthorhombic distortion present across large regions of Bi-2201 phase diagram

Next step: is apparent electronic inversion sym breaking fully explained by this structural effect?
Superconductors: 100 Year History

Pseudogap in cuprates:
- Competing or collaborating?
- Inter-unit-cell order: checkerboards
- Intra-unit-cell order: nematicity, inversion symmetry breaking

Vortex pinning in cuprates & pnictides:
- STM imaging of Ba-122, 3-dim isotropy
- MFM imaging of NdFeAsO, in-plane anisotropy
Interest in High-$T_c$ Cuprates

![Graph showing the number of articles and patents related to high-$T_c$ cuprates over the years. The graph includes lines for INSPEC - total, INSPEC - cuprates, CAS - cuprates, and WPI - patents. A question mark is placed near the graph reading, "funding agency frustration sets in?" ]

2008: A New Revolution in Superconductivity


$LaFeAsO_{1-x}F_x$

$T_c=26K$

[Diagram of the crystal structure of LaFeAsO$_{1-x}F_x$ showing the insulating layer and conducting layer.]

[Graph showing the temperature dependence of $T_{anom}$, $T_{min}$, $T_{onset}$, and $T_c$ as a function of $F^-$ content (atomic fraction).]
Cuprate-Pnictide Comparison

**Cuprate Superconductors**
- antiferromagnetic Mott insulator
- 
  - Carrier concentration
  - Temperature
  - Pseudo-gap
  - "non-Fermi" liquid
  - Fermi liquid?
  - Superconductor

**Iron-Pnictide Superconductors**
- collinear antiferromagnet semimetal
- 
  - Carrier concentration
  - Temperature
  - Pseudo-gap
  - "non-Fermi" liquid
  - Fermi liquid?
  - Superconductor

- $T_c^{\text{max}} \sim 135$ K
- $T_c^{\text{max}} \sim 57$ K
Why the excitement?

1) Physics
   • A second chance to get it right!
   • A foil for cuprates

2) Applications
   • Low anisotropy
   • High $H_{c2}$
   • Strong pinning

SmO$_{0.7}$F$_{0.3}$FeAs wires fabricated by powder-in-tube method

$T_c=52$K, $J_c$ up to 3900 A/cm$^2$, extrapolated $H_{c2}$ up to 120T
($J_c$ within grains $\sim 2\times10^5$ A/cm$^2$)

A Short History of Iron-Pnictide Superconductivity

- e-doped: LaFeAsO$_{1-x}$Fx
- hole-doped: La$_{1-x}$Sr$_x$FeAsO
- SmFeAsO$_{1-x}$Fx
- Gd$_{1-x}$Th$_x$FeAsO
- Tb$_{1-x}$Th$_x$FeAsO
- TbFeAsO$_{1-x}$Fx
- DyFeAsO$_{1-x}$Fx
- Sr$_{1-x}$K$_x$Fe$_2$As$_2$
- Ba$_{1-x}$K$_x$Fe$_2$As$_2$
- Eu$_{1-x}$K$_x$Fe$_2$As$_2$
- Ca$_{1-x}$Na$_x$Fe$_2$As$_2$
- SrCo$_{1-x}$Fe$_2$As$_2$
- BaCo$_{x}$Fe$_{2-x}$As$_2$
- SrNi$_{2-x}$As$_2$
- BaNi$_{1-x}$Fe$_{2-x}$As$_2$
- α-FeSe$_{1-x}$
- FeSe$_{0.5}$Te$_{0.5}$

$T_c$ (K)

2006-7

Feb Mar Apr May Jun Jul Aug Sep Oct Nov

2008
A Long History of Superconductivity

1911 – Kamerlingh Onnes – first superconductivity in Hg

1933 – Meissner – superconductors screen B-field

1952 – Abrikosov – predicted vortices

1957 – Bardeen, Cooper & Schriefer – theoretical understanding

1962 – Josephson – field-dependent tunneling (SQUIDS)

Vortex pinning problem largely solved…
  but still not so many practical applications because T requirements so severe…

1986 – Bednorz & Mueller – high-Tc superconductors

Still not so many practical applications…
  severe vortex pinning problems in cuprates…
  T requirements still non-trivial…

2008 – Hosono – Fe-based high-Tc superconductors

Today’s frontiers:
1. discover higher-Tc materials → need to understand the ones we’ve got
2. improve vortex pinning in high-Tc materials
Outline

Superconductors: 100 Year History

Pseudogap in cuprates:
  • Competing or collaborating?
  • Inter-unit-cell order: checkerboards
  • Intra-unit-cell order: nematicity, inversion symmetry breaking

Vortex pinning in cuprates & pnictides:
  • STM imaging of Ba-122, 3-dim isotropy
  • MFM imaging of NdFeAsO, in-plane anisotropy
Vortex pinning: low anisotropy, high $H_{c2}$

strong pinning, speculation that it comes from nanoscale pinning sites, e.g. Co dopant inhomogeneities $\rightarrow$ need a local tool to study these materials!

Yamamoto, APL 94, 062511 (2009)
Resistivity of our Ba(\(\text{Co}_{x}\text{Fe}_{1-x}\))\(_2\)As\(_2\) single crystals grown by Prof. XianHui Chen

we’re studying this one! 
\(T_c = 25.3\) K

Atomic Resolution Topography

$\text{Ba}(\text{Co}_x\text{Fe}_{1-x})_2\text{As}_2$

$(x=0.1 \text{ nominal}, T_c=25.3\text{K})$
Gap Mapping

measurements at $T=6K$; $k_B T = 0.5$ meV
$dV$ modulation = 1.5 meV

$\Delta = 6.25 \pm 0.73$ meV (12% variation)
Topography

- Scale: 20 nm
- Color scale: 0 Å to 1.5 Å
Vortices at 9T

dl/dV at 5 mV

(approximate coherence peak energy)
Vortices at 6T

dI/dV at 5 mV
(approximate coherence peak energy)
Flux Measurement

9 T

6 T

3.0 nS
0.5 nS
flux measurement

\[ \phi(9T) = 2.05 \times 10^{-15} \text{T} \cdot \text{m}^2 \]

\[ \phi(6T) = 2.17 \times 10^{-15} \text{T} \cdot \text{m}^2 \]

average vortex area = 228 nm\(^2\)

\[ \phi(9T) = 2.05 \times 10^{-15} \text{T} \cdot \text{m}^2 \]

average vortex area = 362 nm\(^2\)

Single magnetic flux quantum: \( \Phi_0 = 2.07 \times 10^{-15} \text{T} \cdot \text{m}^2 \)
Vortex pinning possibilities

(1) no strong pinners
inter-vortex forces dominate
→ lattice formation

(2) strong pinners exist
low anisotropy
→ vortices bend slightly
to accommodate pinners

(3) strong pinners exist
high anisotropy
→ vortices pancake
each pancake pins independently

ideal case
for applications

\( \text{NbSe}_2 \)

\( \text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8 \)
Are Vortices Pinned to Surface Impurities?

\[ 3.0 \text{ nS} \]

\[ 0.5 \text{ nS} \]
Are Vortices Pinned to Surface Impurities?

**Raw Data**

9 T

**Idealized Data**

- Vortex, radius $\xi_0 = 2.76 \text{ nm}$
- Impurity

**Histogram of Distances**

Linear fit!

$f(x) = A x^P$

Fit: $P = 0.96 \pm 0.1$

$\rightarrow$ Vortices are **not** pinned to visible surface impurities
Vortex pinning possibilities

(1) no strong pinners
inter-vortex forces dominate
→ lattice formation

(2) strong pinners exist
low anisotropy
→ vortices bend slightly
to accommodate pinners

(3) strong pinners exist
high anisotropy
→ vortices pancake
each pancake pins independently
Vortex Spectroscopy

dI/dV map at 0 mV

(Fermi level)

measurements at $T=6K$; $k_B T = 0.5 \text{ meV}$
dV modulation = 1.5 meV
Coherence Length

Radially Averaged Zero Bias $dI/dV$ (nS)

$\overline{\xi}_0 = 2.76$ nm
(standard deviation 2.9 Å)

Note: this $\xi_0$ translates to $H_{c2}=43$T
[close to 50T extrapolated, Yamamoto, APL 94, 062511 (2009)]
Superconductors: 100 Year History

Pseudogap in cuprates:
- Competing or collaborating?
- Inter-unit-cell order: checkerboards
- Intra-unit-cell order: nematicity, inversion symmetry breaking

Vortex pinning in cuprates & pnictides:
- STM imaging of Ba-122, 3-dim isotropy
- MFM imaging of NdFeAsO, in-plane anisotropy
Length Scales in Superconducting Vortices

\[ B(r) = \text{field penetration} \]

\[ n_s(r) = \text{density of Cooper pairs} \]

\[ \xi \] = "coherence length" = distance over which Cooper pairs are broken (superconductivity is destroyed)

\[ \lambda \] = "penetration depth" = distance over which magnetic field decays

\[ \Phi = 2.07 \times 10^{-15} \text{T} \cdot \text{m}^2 \]
**Pros and Cons of MFM**

**Tip Geometry**
- **Con**: Imperfectly known
- **Pro**: Up to 20 nm spatial resolution

**Other signals**
- **Con**: See atomic forces too
- **Pro**: Simultaneous topography

**Invasiveness**
- **Con**: Tip exerts force on vortex
- **Pro**: Tip exerts force on vortex

Force between tip and sample:
\[ \mathbf{F} = \nabla (\mathbf{m} \cdot \mathbf{B}) \]

Frequency modulation imaging (directly measures force gradient):
\[ \frac{\Delta \omega}{\omega_0} = \frac{-1}{2k} \frac{dF_{ts}}{dz} \]

- Vertical force gradient \( \rightarrow \) imaging
- Horizontal force \( \rightarrow \) manipulation
F_depin ranges from 4 to 12 pN at 5.5 K

YBa$_2$Cu$_3$O$_{7-d}$ vortices: Probe Bulk Pinning


map anisotropy

fit anisotropy

deduce anisotropy of bulk pinning
Hoffman Lab Force Microscope

- 2 K to above 340 K
- 5 T vertical field
- lateral coarse motion (3 mm x 3 mm) allows imaging of isolated features in addition to bulk materials
- high-resolution, easily modelable tips fabricated in house via focused ion beam

Radius of curvature: 15-25 nm
Cone half-angles: 1-3°
Aspect ratios: 12-18

Versatility:
- vertical or lateral force measurement
- magnetic tips for magnetic imaging and manipulation
- conducting tips for local conductivity imaging and switching
- vertical cantilevers for friction imaging

built by Dr. Jeehoon Kim
Pairing Symmetry

**Conventional Superconductors**
- s wave pairing

**Cuprate Superconductors**
- $d_{x^2-y^2}$ wave pairing
Iron-pnictides: What is the pairing symmetry?

(1) nodeless extended s-wave ($s^\pm$)
- Wang, PRL 102, 047005 (2009)
- Cvetkovic & Tesanovic, EPL 85, 37002 (2009)

(2) nodal s-wave
- Kuroki, PRL 101, 087004 (2008)

(3) nodeless d
- Kuroki, PRL 101, 087004 (2008)

(4) $d_{x^2-y^2}$ order

(5) nodal intraband p order
- Lee & Wen, PRB 78, 144517 (2008)

(6) interband p order

*figures borrowed from from Hicks, … Moler, JPSJ 78, 013708 (2009)*
ARPES: What is the pairing symmetry?

$\text{Ba}_{0.6}\text{K}_{0.4}\text{Fe}_2\text{As}_2$

($T_c = 37\ \text{K}$)

$\text{NdFeAsO}_{0.9}\text{F}_{0.1}$

($T_c = 53\ \text{K}$)

Ding, EPL 83, 47001 (2008)

Kondo, PRL 101, 147003 (2008)
Converging on $s^\pm$ symmetry?

(1) nodeless extended $s$-wave ($s^\pm$)
- Wang, PRL 102, 047005 (2009)
- Cvetkovic & Tesanovic, EPL 85, 37002 (2009)

(2) nodal $s$-wave
- Kuroki, PRL 101, 087004 (2008)

(3) nodeless $d$
- Kuroki, PRL 101, 087004 (2008)

(4) $d_{x^2-y^2}$ order

(5) nodal intraband $p$ order
- Lee & Wen, PRB 78, 144517 (2008)

(6) interband $p$ order

figures borrowed from Hicks, … Moler, JPSJ 78, 013708 (2009)
BUT... Plenty of Evidence For Gap Nodes

• Specific heat in LaFeAsO$_{0.9}$F$_{0.1-\delta}$

• $H_{c1}$ measurements in LaFeAsO$_{0.9}$F$_{0.1}$
  [Ren et al, arXiv: 0804.1726]

• Point contact spectroscopy in LaFeAsO$_{0.9}$F$_{0.1-\delta}$
  [Shan et al, Europhys. Lett. 83, 57004 (2008)]

• $\mu$SR in LaFeAsO$_{1-x}$F$_x$

• NMR in LaFeAsO$_{1-x}$F$_x$
  [Ahilan et al, Phys. Rev. B 78, 100501 (2008),

• NMR in LaFeAsO$_{1-y}$ and NdFeAsO$_{1-y}$

• NMR in FeSe

• Thermal Hall conductivity in Ba$_{1-x}$K$_x$Fe$_2$As$_2$
  [Checkelsky et al, arXiv: 0811.4668]

• Penetration depth $\lambda$ in Ba(Co$_{0.07}$Fe$_{0.93}$)$_2$As$_2$

• Penetration depth $\lambda$ in LaFePO
  [Fletcher et al, arXiv: 0812.3858]

→ What can we contribute?
Vortex Manipulation in NdO$_{1-x}$F$_x$FeAs

- **d large (tip far from sample, small force):** image without disturbing vortex

- **d intermediate:** drag the top of the vortex

- **d small (tip close to sample, large force):** permanently move the entire vortex
Angular dependence in NdO$_{1-x}$F$_x$FeAs

d intermediate: drag the top of the vortex

$\text{0°}
\begin{array}{ccccccc}
& 0° & & & & & \\
& 15° & & & & & \\
& 30° & & & & & \\
& 45° & & & & & \\
& 60° & & & & & \\
\end{array}$

$w = \text{fast scan drag width}$

$vortex \quad \text{pinning site}$

$1 \mu m$
Angular dependence in NdO$_{1-x}$F$_x$FeAs

Burning question:
→ does 4-fold symmetry come from anisotropic defects or from intrinsic pairing property of Fe-based superconductor?
## Cuprate-Pnictide Comparison

<table>
<thead>
<tr>
<th></th>
<th>Cuprate: ( \text{Bi}_2\text{Sr}_2\text{CaCu}<em>2\text{O}</em>{8+d} )</th>
<th>Pnictide: ( \text{BaCo}<em>x\text{Fe}</em>{2-x}\text{As}_2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pseudogap</strong></td>
<td>Broken translational symmetry: “checkers”</td>
<td>Pseudogap not consistently observed.</td>
</tr>
<tr>
<td><strong>Short range order</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Structural</strong></td>
<td>Structure: breaks inversion symmetry</td>
<td>Structure: orthorhombic, but no evidence of inversion symmetry breaking</td>
</tr>
<tr>
<td><strong>Long range order</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
## Cuprate-Pnictide Comparison

<table>
<thead>
<tr>
<th>Vortex pinning</th>
<th>Cuprate: Bi$_2$Sr$_2$CaCu$<em>2$O$</em>{8+d}$</th>
<th>Pnictide: BaCo$<em>x$Fe$</em>{2-x}$As$_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preliminary: vortex pinning anisotropy</td>
<td><img src="image1.png" alt="YBCO" /></td>
<td><img src="image2.png" alt="NdFeAsO" /></td>
</tr>
</tbody>
</table>

- Vortices pinned to surface impurities
- Vortices NOT pinned to surface impurities
Future Directions

**STM**

- NbSe$_2$: understand interplay of SC and CDW in a “simpler” system

**Force Microscope**

- Quantify pinning forces and anisotropies on single vortices

**Spin-polarized STM**

- Search for real space evidence of spin density waves & relation to SC
- Quantify local relationship between broken symmetries & superconductivity

NdFeAsO