Imaging the New Iron-Arsenic High-\(T_c\) Superconductors

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Thanks to:
Outline

Superconductors: Brief History

Iron Pnictides: Revolution in Superconductivity!

→ What are the big outstanding questions?
→ Where do we stand in answering these questions?

STM applied to iron pnictides

• surface considerations
• superconducting gap measurement
• vortex mapping

Direct comparison to cuprates

Outlook
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>Niobium</td>
<td>9.2</td>
<td>0.1944</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>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

$\rightarrow$ Type II Superconductors are generally more useful
Length Scales in Superconducting Vortices

\[ \Phi = 2.07 \times 10^{-15} \text{T} \cdot \text{m}^2 \]

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

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

\[ r = \text{distance from vortex center} \]

- **Coherence length**
  - distance over which Cooper pairs are broken (superconductivity is destroyed)

- **Penetration depth**
  - distance over which magnetic field decays
Vortex Challenges

Normal electrons in vortex core cause dissipation when moved

Apply current $I$: Cooper pairs flow without dissipation

$\rightarrow$ need some mechanism to pin vortices in place

Center of vortex: superconductivity is destroyed $\rightarrow$ costs energy!

so introduce defects where superconductivity is already compromised $\rightarrow$ 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

LHC at CERN
A Long History of Superconductivity

1911 – Kamerlingh Onnes – first superconductivity in Hg ➔ 1913 Nobel Prize
1933 – Meissner – superconductors screen B-field ➔ 2003 Nobel Prize
1952 – Abrikosov – predicted vortices ➔ 1972 Nobel Prize
1957 – Cooper, Bardeen & Schriefer – theoretical understanding ➔ 1973 Nobel Prize
1962 – Josephson – field-dependent tunneling (SQUIDS)

Still not so many practical applications…
History of Superconducting $T_c$

Year of Discovery

Temperature [K]

- HgBaCaCuO
- TlSrBaCuO
- BiCaSrCu$_2$O$_9$
- YBa$_2$Cu$_3$O$_7$
- LaBaCuO$_4$

Materials:
- Hg
- Pb
- Nb
- NbN
- $V_3$Si
- Nb$_3$Sn
- Nb$_3$Ge

Year:
- 1900
- 1920
- 1940
- 1960
- 1980
- 2000

Temperatures:
- 77K LN$_2$
- 4.2K LHe
Pairing Symmetry

Conventional Superconductors
s wave pairing

Cuprate Superconductors
d$_{x^2-y^2}$ wave pairing

Density of States

Energy (meV)
‘Normal’ State

Conventional Superconductors
Normal state: metallic; Fermi liquid

Cuprate Superconductors
Doped antiferromagnetic insulator

![Graph showing resistance vs. temperature for conventional superconductors.]

![Diagram illustrating the transition from an antiferromagnetic insulator to a pseudo-Fermi liquid and then to a Fermi liquid.]

Carrier concentration

![Diagram of the BiO-SrO-CuO$_2$-CaCu$_2$O$_8$ lattice structure.]

E.g.: Bi$_2$Sr$_2$CaCu$_2$O$_8$

(Each Oxygen is thought to donate 2 holes)
3-Dimensional Cuprate Phase Diagram

- 2 known phases
- AF
- Superconductivity
Too Much Phase Space

"HERE BE DRAGONS"
Applications of Cuprate Superconductors

Maglev Trains: currently in operation at Shanghai Pudong Airport

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

Semiconductors:

$Billions

$Billions

Year

Year

medical
industrial
transportation
green
energy
electronics
(Conectus, 2004)

(Sakurai, 1999)
Material Considerations

**Bi$_2$Sr$_2$CaCu$_2$O$_{8+d}$/Ag wires**

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

**YBa$_2$Cu$_3$O$_{7-d}$ tapes**

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

Trouble With Vortices

\[ H_{c2} \]

\[ H^* \text{ (where vortices move)} \]

Larbalestier, Nature 414, 368 (2001)
2008: A New Revolution in Superconductivity


LaFeAsO$_{1-x}$F$_x$

$T_c$=26K

LaFeAsO$_{1-x}$F$_x$

insulating layer

conducting layer

Temperature (K)

F$^-$ content (atomic fraction)
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

$T_c=52K$, $J_c$ up to 3900 A/cm$^2$, extrapolated $H_{c2}$ up to 120T

($J_c$ within grains $\sim 2 \times 10^5$ A/cm$^2$)

A Short History of Iron-Pnictide Superconductivity

$T_c$ (K)

- La$_{1-x}$Ni$_x$Fe$_2$As$_2$
- SrNi$_2$As$_2$
- Eu$_{1-x}$LaxFe$_2$As$_2$
- Ca$_{1-x}$Na$_x$Fe$_2$As$_2$
- SrCo$_{1-x}$Fe$_2$As$_2$
- Li$_{1-x}$FeAs
- LaO$_{1-x}$NiP
- LaONiP
- BaNi$_2$P$_2$
- LaOFeP
- LaO$_{1-x}$NiBi
- α-FeSe$_{1-x}$
- α-FeSe$_{0.5}$Te$_{0.5}$

2006-7

“Tsunami of Papers”

# of papers / month

Mar Apr May Jun Jul Aug Sep Oct

20 40 60 80 100
(1) What is the pairing symmetry?

(2) What is the role of spin?

(3) Quantify & understand $H_{c2}$ and vortex pinning?
(1) What is the pairing symmetry?

(2) What is the role of spin?

(3) Quantify & understand $H_{c2}$ and vortex pinning?
Theory: What is the pairing symmetry?

(1) **nodeless extended s-wave (s±)**
- 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)*
Scanning SQUID: what is the pairing symmetry?

Polycrystalline material would have many grain boundaries. In some symmetry scenarios, e.g. $d_{x^2-y^2}$, some grain boundaries would flip sign of order parameter → trap fractional flux!

$\text{NdFeAsO}_{0.94}\text{F}_{0.06}$ ($T_c = 48 K$)
No Fractional Vortices Observed!

Hicks, ... Moler, JPSJ 78, 013708 (2009)
ARPES: What is the pairing symmetry?

Ba$_{0.6}$K$_{0.4}$Fe$_2$As$_2$ (T$_c$ = 37 K)

Ding, EPL 83, 47001 (2008)

NdFeAsO$_{0.9}$F$_{0.1}$ (T$_c$ = 53 K)

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]
Big Unanswered Questions

(1) What is the pairing symmetry?

(2) What is the role of spin?

(3) Quantify & understand $H_{c2}$ and vortex pinning?

![Diagram](image)

Cuprates

- AF inst.
- Pseudo-gap
- “non-Fermi” liquid
- Fermi liquid?
- Superconductor

LaFeAsO$_{1-x}$F$_x$

- $T_{anom}$
- $T_{min}$
- $T_{onset}$
- $T_c$

Temperature (K) vs. $F^-$ content (atomic fraction)
Neutron Scattering: What is the role of spin?

LaO$_{1-x}$F$_x$FeAs

- $x=0$: Structural ordering: 138K
- $x=0$: Collinear antiferromagnetic spin ordering: 137K

Doping suppresses both, allows superconductivity.

de la Cruz et al, Nature 453, 899 (2008)
Cuprate vs. Pnictide Spin Comparison

CUPRATE

\[ Q = (\pi, \pi) \]

AF

IRON ARSENIDE

\[ Q = (0, \pi) \]

SDW

- Oxygen ions
- Copper ions
- Arsenic ions
- Iron ions
Inelastic Neutron Scattering

magnetic resonance energy \sim 5k_B T_c

\textbf{BaFe}_{1.84}\textbf{Co}_{0.16}\textbf{As}_2

Lumsden, arXiv:0811:4755
(1) What is the pairing symmetry?

(2) What is the role of spin?

(3) Quantify & understand $H_{c2}$ and vortex pinning?
Vortex pinning: low anisotropy, high $H_{c2}$

Cuprate Superconductors

Pnictide Superconductors

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

Yamamoto, APL 94, 062511 (2009)
(1) What is the pairing symmetry?

(2) What is the role of spin? \( \rightarrow \) will have to wait...

(3) Quantify & understand \( H_{c2} \) and vortex pinning?
Introduction to STM

- Sample
- Tip

Sample LDOS under tip

TIP DOS

$E_F$ (sample)

$E_F$ (tip)

$G$
Introduction to STM

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

Tip vacuum

Sample LDOS under tip

$E_F$ (tip)

$E_F$ (sample)

Sample

Tip
Introduction to STM

$$\frac{dI}{dV} \propto \text{LDOS}(eV)$$

Tip modulate by $dV$

TIP DOS

Sample LDOS under tip

Sample

Tip

$V$

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

- likely structural transition
- likely magnetic transition
- superconducting transition

Resistivity of our $\text{Ba(Co}_{x}\text{Fe}_{1-x})_{2}\text{As}_2$ single crystals grown by Prof. XianHui Chen

$T_c = 25.3$ K

Ba(Co\(_x\)Fe\(_{1-x}\))\(_2\)As\(_2\)  
(x=0.1 nominal, T\(_c\)=25.3K)
\( \text{Ba(Co}_{x}\text{Fe}_{1-x})_2\text{As}_2 \) cleavage plane?

- **Ba** (2+)
- **As** (1-)
- **Fe**

### 

**all Ba remain?**
- Top Ba layer has charge 1+

**all Ba removed?**
- Top As layer has charge 1-

\( \frac{1}{2} \) Ba removed, \( \frac{1}{2} \) Ba remain?
- Top layer is charge neutral
Fourier Transform Analysis

Raw data:

Fourier transform

Filter

inverse Fourier transform
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

20 nm

1.5 Å

0 Å
Vortices at 9T

dI/dV at 5 mV
(approximate coherence peak energy)
Vortices at 6T

dl/dV at 5 mV
(approximate coherence peak energy)

20 nm
Flux Measurement

9 T

6 T

3.0 nS

0.5 nS
average vortex area = 228 nm$^2$
$\Rightarrow \phi(9T) = 2.05 \times 10^{-15}$ T$\cdot$m$^2$

average vortex area = 362 nm$^2$
$\Rightarrow \phi(6T) = 2.17 \times 10^{-15}$ T$\cdot$m$^2$

Single magnetic flux quantum: $\Phi_0 = 2.07 \times 10^{-15}$ T$\cdot$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?

![Image of vortices pinned to surface impurities]

- 9 T

Scale: 10 nm

Color scale: 0.5 nS to 3.0 nS
Are Vortices Pinned to Surface Impurities?

Raw Data

Idealized Data

Histogram of Distances

\[ f(x) = Ax^P \]

Fit: \( P = 0.96 \pm 0.1 \)

\( \xi_0 = 2.76 \text{ nm} \)

\( \text{Impurity} \)

\( \text{Vortex} \)

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
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each pancake pins independently

NbSe$_2$

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

Bi$_2$Sr$_2$CaCu$_2$O$_8$
What we know so far...

• We have a superconducting gap, in agreement with ARPES

• We have vortices, which are strongly pinned in bulk
Vortex Spectroscopy

dl/dV map at 0 mV
(Fermi level)

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

Radially Averaged Zero Bias $\frac{dI}{dV}$ (nS)

Note: this $\xi_0$ translates to $H_{c2} = 43$T
[close to 50T extrapolated, Yamamoto, APL 94, 062511 (2009)]
**Compare to Conventional s-wave Vortices**

**Theory:** \( E = \frac{1}{2} \Delta^2 / \varepsilon_F \)

Caroli, deGennes, Matricon, PRL 9, 307 (1964)

**STM experiments on NbSe\(_2\)**


\[ T_c = 25 \text{ K}; \text{ measurement } T = 6 \text{ K} \quad \Rightarrow T \sim T_c/4 \]

\[ T_c = 7.2 \text{ K}; \text{ measurement } T = 1.45 \text{ K} \quad \Rightarrow T \sim T_c/5 \]
Residual resistivity: $\rho_0 = 0.23 \text{ m}\Omega\cdot\text{cm}$

Hall coefficient: $R_H = 11 \times 10^{-9} \text{ m}^3/\text{C}$

$\rightarrow$ electronic mean free path:

$$\ell = \frac{\hbar (3\pi^2)^{1/3}}{(e^2 n^{2/3} \rho_0)} \sim 81 \text{ Å}$$

Compare to coherence length: $\xi_0 = 27.6 \text{ Å}$

$\rightarrow$ Clean limit

$\rightarrow$ Wouldn’t expect suppression of s-wave vortex core states
Compare to $d$-wave Vortex Spectroscopy

$\text{BaCo}_x\text{Fe}_{2-x}\text{As}_2$

\[ \frac{dI}{dV} \text{(nS)} \]

Sample Bias (mV)

\[ \frac{dI}{dV} \text{(nS)} \]

\[ H = 7.25 \text{T} \]

$V_{\text{sample}}$ (mV)

\[ E \sim \Delta/4 \]

Pan, PRL 85, 1536 (2000)

$\text{Bi}_{2}\text{Sr}_{2}\text{CaCu}_2\text{O}_{8+d}$

\[ \frac{dI}{dV} \text{(nS)} \]

$H = 0 \text{T}$

$H = 6 \text{T}$

\[ T = 4.2 \text{K} \]

Maggio-Aprile, PRL 75, 2754 (1995)

\[ \Delta/4 \]

\[ V_{\text{sample}} \text{[mV]} \]

\[ T_{\text{sample}} \text{[mV]} \]

measurements at $T=6K$; $k_B T = 0.5 \text{ meV}$

d$V$ modulation = 1.5 meV
Compare to Theoretical $d$-wave Vortex Shape

BaCo$_x$Fe$_{2-x}$As$_2$

10 nm

0 nS [ ] 1.5 nS


Ichioka, PRB 53, 15316 (1996)

Franz & Tesanovic, PRB 53, 15316 (1996)
Are Vortices Isotropic?

Filter impurities

Average vortices

![Image of vortices](image)

![Graph of normalized conductance vs. radial distance](graph)

- Parallel to crystal axis (4-fold avg.)
- 45° rotated (4-fold avg.)

\[ \frac{1}{\text{Normalized Conductance}} \]

Radial Distance (nm)
STM To-Do List

- Better surface characterization:
  cleave temperature dependence, a la Pennec et al, PRL 101, 216103 (2008)

- Normalize to higher T

- Data at lower T, to resolve multiple gaps,
  see how each behaves in field
  → STM currently off-line for upgrade to $^3$He fridge
STM To-Do List

- Quasiparticle interference

s± symmetry scenario:
predicted scattering from magnetic impurities

- $q=(2\pi, 0)$ scattering $\Rightarrow$ STRONG

- $q=(\pi, \pi)$ scattering $\Rightarrow$ weak

[Note: Pereg-Barnea & Franz similarly predicted for d-wave scenario,
$+/+ \text{ scattering}$ enhanced in B, $+/- \text{ scattering}$ unaffected by B
PRB 78, 020509 (2008). ]

- Repeat impurity measurements, compare to preliminary theory
  [Michael Lawler, Eun-Ah Kim]

- Compare vortex core state measurements to theory
  [J.X. Zhu, C.S. Ting]
## Cuprate-Pnictide Comparison

<table>
<thead>
<tr>
<th></th>
<th>Cuprate: Bi₂Sr₂CaCu₂O₈+d</th>
<th>Pnictide: BaCoₓFe₂₋ₓAs₂</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>phase diagram</strong></td>
<td><a href="#">Temperature diagram</a></td>
<td><a href="#">Phase diagram</a></td>
</tr>
<tr>
<td><strong>ground state</strong></td>
<td>antiferromagnetic Mott insulator</td>
<td>itinerant antiferromagnet semimetal</td>
</tr>
<tr>
<td><strong>gap symmetry</strong></td>
<td>d-wave</td>
<td>s± ??</td>
</tr>
<tr>
<td><strong>anisotropy, γ</strong></td>
<td>~ 50</td>
<td>~ 1-3</td>
</tr>
<tr>
<td><strong>optimal T&lt;sub&gt;c&lt;/sub&gt;</strong></td>
<td>91 K</td>
<td>25.3 K</td>
</tr>
</tbody>
</table>

Ni, Canfield, *et al*, arXiv:0811.1767
## Cuprate-Pnictide Comparison

<table>
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<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>superconducting gap, (\Delta)</strong></td>
<td>(\Delta \sim 33) meV (2\Delta/k_B T_c \sim 6-10)</td>
<td>(\Delta = 6.25) meV (2\Delta/k_B T_c = 5.73)</td>
</tr>
<tr>
<td><strong>gap inhomogeneity</strong></td>
<td>(\sigma \sim 7) meV (\sigma/\Delta \sim 21%)</td>
<td>(\sigma = 0.73) meV (\sigma/\Delta = 12%)</td>
</tr>
<tr>
<td><strong>coherence length, (\xi_0)</strong></td>
<td>2.2 nm</td>
<td>2.7 nm</td>
</tr>
<tr>
<td><strong>vortex pinning</strong></td>
<td><img src="image" alt="vortices pinned to surface impurities" /></td>
<td><img src="image" alt="vortices NOT pinned to surface impurities" /></td>
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Scanning Probe Microscopy

STM

Spin-Polarized STM

Magnetic Force Microscope

all of the data in this talk

coming on line in the next 6 months - year