Tunneling in High-Temperature Superconductors: Spectroscopy of Broken Symmetries

Laura H. Greene
Department of Physics
University of Illinois at Urbana-Champaign

Experiment:
M. Aprili, M. Covington, E. Badica, D. E. Pugel, H. Aubin,
P. Hentges, Y.-M. Xia and M. B. Salamon
Dept. of Physics, University of Illinois at Urbana-Champaign

Sha Jain and D. G. Hinks,
Materials Science Division, Argonne Nat'l Lab

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J. A. Sauls, M. Fogelström, D. Rainer
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Lecture II: NSF Boulder Summer School for Condensed Matter Physics, July, 2000
Magnitude, Hysteresis and Orientation of Field
2. Damage and Doping
1. Crystallographic Orientation
ABS Tunneling Spectroscopy

Origin of the surface-induced Andreev bound states (ABS)
4. Andreev bound state diagnostics
3. Origin of the Andreev bound state (ABS)
2. Junction Formation and Diagnostics
1. Materials Growth
Experimental Foundation

Symmetry, broken symmetry and d-wave SC

Outline (lecture II)

Dot breaks symmetry:

Circle (rotation symmetry):

measureable change
Changing a coordinate produces a
The symmetry of the state in lower
coordinates
Typically inhomogeneous w/:
Broken Symmetry States:

Symmetry / Broken Symmetry

same as that of the Hamiltonian
The symmetry of the state is the
Homogeneous w/ coordinates

(distance, angle, phase, time...)
Driven Gauge: Laser

Gauge:

Superconductor (T<\text{T}_c)

Normal Metal (T>\text{T}_c)

\text{T}_c > \text{T}_f

\text{Ferromagnet (T>\text{T}_f)}

\text{Paramagnet (T<\text{T}_f)}

\text{Time Reversal:}

\text{Symmetry:}

\text{Broken Symmetry}

\text{Phase Transition} & \text{A Change in Macroscopic Properties}

\text{Symmetry} & \text{Characterized by "Rigidity" of Coordinates}

\text{Spontaneous} & \text{Phase Transition}

\text{Coherent} & \text{Incoherent}

\text{Coherent pairs in a Superconductor} & \text{Electron waves in a metal}

\text{Wave during half-time} & \text{Fans at football game}

\text{Laser} & \text{Lightrub}

\text{Phase Coherence}
Film Growth: Off-Axis Planar Magnetron Sputter Deposition:

Films: (target stoichiometry) Ar:O plasma

Sputter gun

Stoichiometric Target: YBa$_2$Cu$_3$O$_7$
(or doped species)

Heater

Reproducible films of (001), (100) and (103) and (110)-oriented YBa$_2$Cu$_3$O$_7$, (Y$_x$Pr$_{1-x}$)Ba$_2$Cu$_3$O$_7$, YBa$_2$(Cu$_x$Ni$_{1-x}$)$_3$O$_7$, YBa$_2$(Cu$_x$Zn$_{1-x}$)$_3$O$_7$

Materials Analysis includes:
- Electronic transport (resistivity vs. temperature, tunneling)
- Magnetization (susceptibility vs. temperature)
- Structural analysis (XRD, RBS, SEM, AFM, etc....)
- Electron Paramagnetic Resonance (EPR) *

BSCCO single crystals: Jain & Hinks, ANL
Traveling solvent float zone furnace
Possible Orientation of CuO₂ Planes

Film Quality -- snapshot:

Resistivity of (110) YBCO

Anisotropy $\sim 45^\circ$
(comp. to Single Xtal)

$\rho$ [m$\Omega$cm]

$\rho$ [$\mu$Ωcm]

Pr-doped YBCO:

Pr substitutes for Y, causes a "buckling" of the CuO$_2$ planes
⇒ potential scattering
⇒ lowers $T_c$ (in d-wave case; eg.)

<table>
<thead>
<tr>
<th>$X$</th>
<th>$T_c$ (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>90</td>
</tr>
<tr>
<td>0.2</td>
<td>70</td>
</tr>
<tr>
<td>0.4</td>
<td>45</td>
</tr>
<tr>
<td>0.5</td>
<td>20</td>
</tr>
</tbody>
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Our experiments on:
- C-axis (001)
- a-b-plane (110), (110), (03)
- oriented thin films

* Controversial interpretation since ~2 mos. ago:
  Pr → Ba; reduces $T_c$ (Pr→Y; no $T_c$ reduction)

$T_c$ & $\rho$ (comp. to single crystal)
Tunnel Junction Fabrication / Diagnostics

- Pb counter-electrodes evaporated ex-situ.
- ~½ hour from sputter chamber to liquid-N₂

TUNNELING verified by:
* Pb counter electrode: low-leakage Pb gap (~1% @ 4.2K) & phonons
* Junction resistance: scales with 1/A₉
* Little to no temperature dependence
* REPRODUCIBILITY: including film-to-film

Also: Normal-metal counter-electrode (insulator formed by chemical techniques)

1. Covington ... Mirkin (NWU, Chemistry) PRL 73 281 (1994)
   Chemical modification using SAM's / Cu
2. Hentges, Pofford, Westwood (UIUC, Chemistry) APS March '00
   Chemical modification: ZrO₂ / Ag
3. Badica, Rubin APS March '00
   / Bi
4. Rubin M⁵S-HTSC-VE '99
   / CaF₂ / Ag on BSCCO single crystals

Overview of Tunnel Junctions

Pb / (001), (100), (103) and (110) oriented YBa₂Cu₃O₇

Many phenomena may produce a ZBCP (zero-bias conductance peak) in the tunneling conductance:

e.g.: magnetic/spin-flip scattering, Proximity/Josephson effects, shorts/pinholes through barrier, Cooper-pair tunneling, Reflectionless tunneling, Multiple Andreev reflections (MAR), Inelastic processes, etc.

Diagnostics required to test if ZBCP is an ABS (Andreev bound state); intrinsic to d-wave SC.
Zero Bias Conductance Peak (ZBCP) is an Andreev Bound State (ABS)

As shown by the data dependences upon:

1. **Crystallographic orientation**
   - Only seen in ab-plane tunneling (not in c-axis)
   - Not seen in specular (100) a-axis tunneling (Aiff, et al.)

2. **Temperature**
   - Split in ZBCP below $T_s$
   - Zero-bias conductance $\sim 1/T$ below 40K, above $T_s$

3. **Magnetic Field**
   - Field Evolution
   - Saturation effects
   - Field Scale
   - Angular dependence / Orientation dep
   - Hysteresis

4. **Doping and disorder**
   - ZBCP reduces in size and disappears with increased doping and ion-induced damage.
   - This is shown to be a DoS effect (follows gap disorder dependence)

5. **Penetration depth** (Walter et al.)

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**QUASI-PARTICLE (QP) TUNNELING SPECTROSCOPY**

*Conductance vs. Bias (Voltage) or QP DoS vs. Energy*

DoS $\uparrow$

![Graph 1: Expected for bulk d-wave](image1.png)

0

Expected for bulk d-wave

![Graph 2: Observed for ab-plane tunneling](image2.png)

0
eV.

Observed for ab-plane tunneling

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The observed **Zero-Bias Conductance Peak (ZBCP)** is a

**Surface-Induced Andreev Bound State (ABS).**

Intrinsic to an unconventional (e.g., d-wave) superconductor at a symmetry-breaking surface (i.e., 110-direction of YBCO)

**References:**

- Buchholtz, Zwicknagl (1982): For p-wave
- C.-R. Hu (1994): Applied to d-wave
- Buchholtz, Palumbo, Rainer, Sauls (1995) Thermodynamics
ANDREEV REFLECTION: For an $\text{Sinterface}$ (No N)
Conventional (s-wave) superconductor:

- Insulator or Vacuum
- Electrons, holes and cooper pairs are simply reflected

$|\psi|^2 = \text{Superconducting Order Parameter}$

$|\psi|^2 \sim \# \text{ of Cooper Pairs}$

ANDREEV REFLECTION: For an $\text{NS interface}$
Conventional (s-wave) superconductor:

- From Normal metal: Electron Retroreflected as a hole
- From Superconductor Cooper Pairs Broken

$\psi = \text{Superconducting Order Parameter}$

$|\psi|^2 \sim \# \text{ of Cooper Pairs}$

PROXIMITY EFFECT
Surface-Induced Andreev Bound States:

s-wave:
No Andreev Reflection
(+ → + in order parameter)
Cooper Pairs not Broken

d-wave:
Strong Andreev Reflection
(+ → − in order parameter)
Cooper Pairs Broken

Electrons and Holes Created at Interface are BOUND between interface and Order Parameter
Creating the Andreev Bound States

ORIGIN OF ANDREEV BOUND STATE

Quasi-Classical Trajectory along D:

Sign-change of Order Parameter is only Boundary Condition
Solution to Andreev Equations:
Quasiparticle Bound State at surface (decay $\sim \xi_0$)
Tunneling into BSCCO single crystals
Orientational dependence in ab-plane

\[ G \text{ (mS)} \]
\[ V \text{ (mV)} \]

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

[100] [110]

\[ G/G(60\text{mV}) \]

(b) c-axis

(a) ab-plane

Tunneling into Y_{1-x}Pr_{x}Ba_{2}Cu_{3}O_{7} (T=1.5K; H=0.2T)

Voltage (mV)

0.0 0.3 0.6 0.9 1.2

-80 -60 -40 -20 0 20 40 60 80

0.5 0.2 0.4
Tunneling Conductance of YBCO vs Doping/Disorder:

Normalized Conductance

Voltage (mV)

$0.0 \quad 0.2 \quad 0.4 \quad 0.6 \quad 0.8 \quad 1.0 \quad 1.2 \quad 1.4 \quad 1.6$

Normalized Conductance
Scaling of the GLF with $T_c$
in ab-Oriented YBCO Thin Films:
Pr, Zn and Ni-doping

QP scattering rates measured by
ABS height $\rho (T)$
Resitivity vs. temperature $\rho (T)$

SCALE WITH Damage

Comparison between Theory and Experiment

Magnetic field dependence:
M. Covington, LGH, PRB (preprint), etc.,...
Magnetic Field Evolution of ZBCP

![Graph showing magnetic field evolution of ZBCP with peak position and applied magnetic field (H) on a graph. YBCO/Cu and YBCO/Pb are compared.](image)

Magnetic field dependence: Magnitude

![Graph showing magnetic field dependence with splitting (δ) and applied magnetic field (Tesla). YBCO/Cu and YBCO/Pb are compared.](image)

Fit: **Doppler shift and pair-breaking at H_c**

\[ \delta \sim v_F \cdot P_s \]

References:

M. Covington, L.H.G, PRB (preprint), etc...
Fogelstrom, Rainer & Sauls PRL 79 281 (1997)
Covington et al., PRL 79 277 (1997) etc..
Field Scales for LOW applied H

Experiment:
\[ \delta = \frac{1.5 \text{meV}}{\text{Tesla}} \cdot H = \Delta_0 \frac{H}{H_{\text{exp}}} \]

for \( \Delta_0 \sim 1 \text{meV} \) \( H_{\text{exp}} \sim 10 \text{T} \)

compare

1. Magnetic (Spin-flip/Zeeman) Scattering [Anderson; Appelbaum (67)]
   \[ \delta = 9 \mu_B H = \Delta_0 \frac{H}{H_{\text{mag}}} \]
   for \( s = 2 \)
   \( H_{\text{mag}} \sim 125 \text{T} \)

2. Doppler shift [Shown by: Fogelström et al. (97)]
   \[ \delta = \frac{\psi}{c} \nu F H \lambda \sin \phi_c = \Delta_0 \frac{H}{H_{\text{Dop}}} \]
   for \( \phi = 10^\circ \)
   \( H_{\text{Dop}} \sim 1-10 \text{T} \)

Field scale of Experiment is consistent with Doppler shift.

Magnetic field dependence: Hysteresis
M. Aprili, E. Badica, LHG, PRL 83, 4630 (1999)

Consistent with Vortex Pinnning near Surface
verified by: Krupke & Deutscher
PRL 83, 4634 (1999)
Model for Hysteresis
J. Sauls

\[ J_{\text{surface}} = J_{\text{screening}} - J_{\text{vortices}} \]

Vortex distance: \( d \sim (\phi_0 / H)^{1/2} \)
- With increasing \( H_{\text{appl}} \) at low field, \( J_{\text{surf}} \sim J_{\text{screening}} \)
- With decreasing \( H_{\text{appl}} \) from higher field
  - Vortices separate due to magnetic pressure, and are driven towards interface
  - Surface pinning, enhanced by disorder, causes vortices to accumulate at interface

\( J_{\text{surface}} \) becomes significantly reduced by \( J_{\text{vortices}} \)

Magnetic field dependence: Orientation
M. Aprili, E. Badica, LGH, PRL 83, 4630 (1999)

Splitting \( \propto \nabla F \cdot P_s \)
(QP Fermi velocity
Superfluid momentum)

Highly - anisotropic QP transport
ABS carry current parallel ab-planes (not in c-axis direction)

verified by: Kruppek & Deutscher
PRL 83, 4634 (1999)
CONCLUSIONS II

1. Control of materials and junction fabrication is crucial to physics.
   ⇒ Materials / Junction Diagnostics Crucial III!

2. In-plane tunneling into Pr, Ni and Zn-doped, and ion-irradiated
   YBa$_2$Cu$_3$O$_7$ shows $\Delta \sim T_c$
   ⇒ Superconducting state is probed (so can do spectroscopy)

3. ZBCP diagnostics, (i.e., dependencies, as listed below) prove:
   ⇒ The ZBCP is an Andreev Bound State, which must exist at the
     surface of an unconventional superconductor.

4. ABS Tunneling Spectroscopy:
   - Crystal orient: $d$-wave
   - Doping & damage: QP scattering rates below $T_c$
   - $H_{appl}$ magnitude: Doppler shift / pair breaking
   - $H_{appl}$ hysteresis: Vortex pinning by surface and defects
   - $H_{appl}$ angle: Anisotropy of QP transport

Tunneling is a Powerful Phase-Sensitive Probe of Unconventional Superconductivity