High-Temperature Superconductors: Playgrounds for Broken Symmetries

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Outline:

- Superconductivity
- Broken Symmetries
- Andreev Reflection
- Planar Tunneling Spectroscopy
- Controversies in observing Andreev Bound State splittings (tunneling cone and atomic-scale disorder?)
- Open questions
Superconductivity (Webster):

"An electronic state of matter characterized by zero resistance, perfect diamagnetism, and long-range quantum mechanical order."

This means phase coherence, which can be thought of as broken gauge symmetry.
### Definitions of Symmetry and Broken Symmetry

<table>
<thead>
<tr>
<th><strong>Symmetry State</strong></th>
<th><strong>Broken Symmetry State:</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Homogeneous w.r.t. coordinate</td>
<td>Typically inhomogeneous w.r.t. coordinate (distance, angle, phase, time, .. )</td>
</tr>
</tbody>
</table>

“The symmetry of the state is the same as that of the Hamiltonian”

“The symmetry of the state is lower than that of the Hamiltonian”

Changing the coordinate does not produce a measurable change

Changing a coordinate produces a measurable change
### Some examples of Broken Symmetries

<table>
<thead>
<tr>
<th>Symmetry:</th>
<th>Symmetric State</th>
<th>Broken Symmetry State</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Circular</strong></td>
<td>![Red Circle]</td>
<td>![Red Circle]</td>
</tr>
<tr>
<td><strong>Translational:</strong></td>
<td>Fluid</td>
<td>Solid</td>
</tr>
<tr>
<td></td>
<td>![Fluid Image]</td>
<td>![Solid Image]</td>
</tr>
<tr>
<td><strong>Time Reversal:</strong></td>
<td>Paramagnet (T&gt;Tₖ)</td>
<td>Ferromagnet (T&lt;Tₖ)</td>
</tr>
<tr>
<td></td>
<td>![Paramagnet Image]</td>
<td>![Ferromagnet Image]</td>
</tr>
<tr>
<td><strong>Gauge</strong> (spontaneous)</td>
<td>Metal (T&gt;Tₖ)</td>
<td>Superconductor (T&lt;Tₖ)</td>
</tr>
<tr>
<td></td>
<td>![Metal Image]</td>
<td>![Superconductor Image]</td>
</tr>
<tr>
<td><strong>Gauge</strong> (driven, not spontaneous)</td>
<td>Light bulb</td>
<td>Laser</td>
</tr>
<tr>
<td></td>
<td>![Light Bulb Image]</td>
<td>![Laser Image]</td>
</tr>
</tbody>
</table>
Some Ramifications of Broken Gauge Symmetry

<table>
<thead>
<tr>
<th>Photons (driven)</th>
<th>Electrons (spontaneous)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Single-Slit</strong></td>
<td>rf Squid:</td>
</tr>
<tr>
<td>Diffraction:</td>
<td>V</td>
</tr>
<tr>
<td></td>
<td>H</td>
</tr>
<tr>
<td></td>
<td>××××</td>
</tr>
<tr>
<td></td>
<td>V</td>
</tr>
<tr>
<td></td>
<td>H</td>
</tr>
</tbody>
</table>

| Double-Slit      | dc Squid:               |
| Diffraction:     | V                        |
|                  | H                        |
|                  | ××××                      |
|                  | V                        |
|                  | H                        |

Intensity

Electrons (spontaneous)

Intensity
This strongly correlated electronic state results in an energy gap

Energy Gap = 2\Delta

\[ \text{Energy ~ binding energy of Cooper Pair} \]

\[ \text{Density of electronic states} \]
Tunneling: The SIN Tunnel Junction

**Band Diagrams:**
Density of states, \( N(E) \) vs. Energy, \( E \)

- **Empty**
  - \( V = 0 \)
  - \( E \ll E_F \)

- **Full**
  - \( V \neq 0 \)
  - \( E \simeq E_F \)

**Insulator**

**Normal Metal**

**Superconductor**

**Transport:**

**Current:**

\[
I(V) \propto V
\]

**Conductance:**

\[
G(V) = \frac{dI}{dV}
\]

**Tunneling:** The SIN Tunnel Junction

(Conventional)
Measured Tunneling Conductance of a High-Temperature Superconductor

The central peak is due to the broken reflection symmetry of the superconducting order parameter.

YBa$_2$Cu$_3$O$_7$
ab-plane tunneling
Superconductor:

\[ N(E) \Rightarrow \begin{array}{c}
\uparrow \\
\downarrow \\
\end{array} \rightarrow \begin{array}{c}
\uparrow \\
\downarrow \\
\end{array} \]

Energy Gap

\[ 2\Delta \]

Some possible symmetries:

- \textit{s-wave}:
  \[ E_F \]

- \textit{anisotropic s-wave}:
  \[ E_F \]

- \textit{d-wave}:
  \[ E_F \]

\textit{Conventional}:

\textit{Unconventional}:

\[ BCS: \quad N(E) = \frac{N(0) E}{(E^2 - \Delta^2)^{1/2}} \]
ORIGIN OF ANDREEV BOUND STATE

Cooper Pair Quasi-Classical Trajectory along D:

Sign-change of Order Parameter is only Boundary Condition

Solution to Andreev Equations:
Quasiparticle Bound State at surface (decay $\sim \xi_0$)

(110) surface

$\sim \xi_0$

DoE (E=0)

$x$

eV

DoE

$\sim \xi_0$
ANDREEV REFLECTION: For an NS interface
Conventional (s-wave) superconductor:

From Normal metal:
Electron Retroreflected as a hole

From Superconductor
Cooper Pairs Broken

\[ \psi = \text{Superconducting Order Parameter} \]
\[ |\psi|^2 \sim \text{# of Cooper Pairs} \]
Energy Scales for Andreev Reflection

\[ E_F (\text{few V}) \]

\[ \Delta (\text{few mV}) \]
QP scattering in a conventional (s-wave) superconductor:

- Quasiparticles are simply reflected from surfaces or impurities.
- Insulator or Vacuum
  - Surface
- S-wave superconductor
  - Impurity

\[ \psi = \text{Superconducting Order Parameter} \]
\[ |\psi|^2 \sim \# \text{ of Cooper Pairs} \]
\[ |\psi|^2 \text{ ~ # of Cooper Pairs} \]

NO Pair Breaking (Anderson Theorem)
QP scattering in an unconventional (d-wave) superconductor: Andreev Bound States and Impurity Bound States
Magnetic Field Dependence

(103) YBCO / Pb

T = 0.4 K

H = 0.13 T

5.0 T

Conductance (mS)

Voltage (mV)
ORIGIN OF ABS FIELD SPLITTING:

ABS carry current along the interface

Applied Magnetic field, $H_{\text{appl}}$, induces a Doppler Shift:

$$\delta = \delta_s + \left(\frac{e}{c}\right) v_F \lambda \sin \phi_c H_{\text{appl}}$$

$\delta = \text{ABS splitting}$

$\lambda =$ penetration depth

$v_F =$ of tunneling electrons

$\phi_c =$ tunneling cone

Magnetic fields intrinsically break time reversal symmetry, Here, field-driven BTRS is detected by a splitting of ZBCP.

$\therefore$ Splitting of the ABS in ZERO field

$\Rightarrow$ SPONTANEOUSLY

Broken Time-Reversal Symmetry
Spontaneous splitting of ZBCP ($H_{\text{appl}} = 0$):

Consistent with **Broken Time Reversal Symmetry** (BTRS) arising from the formation of a sub-dominant OP (at low temperature, the QPs in the ABS condense into a Cooper channel that is not $dx^2-y^2$, discussed next)

Other models for the spontaneous splitting exist:

Morr & Demler, cond-mat/0010460:


verified by:
- Krupke & Deutscher PRL **83**, 4364 (1999)
Mixed States:

- $s$
- $d$
- $s+d$
- $d+is$

*Broken Time-Reversal Symmetry (magnetism)*
Comments / observations on zero-bias conductance peak splittings

A. For nominally-doped materials, the spontaneous and field-induced splittings are either seen together or no (they go hand-in-hand).

B. There are two cases in which the splittings are not observed:
   1. A narrow tunneling cone
   2. Atomic scale disorder.
NEW junction Fabrication Technique ➔ Narrow Tunneling Cone

Gap-like feature is low, with spectral weight at higher energies

Hydrolysis and Condensation of ultra-pure Zr2(Oprn)16

Provides ultra-thin, pinhole-free zirconia layer

Maintains atomic-scale smoothness on film facets

Data consistent with a small tunneling cone
Model I (for sharp-featured junctions): Tunneling cone can act as a filter

Fogelström et al. PRL (1997)

\[ G_s(\varepsilon) \propto \int d\theta N(\theta, \varepsilon).D(\theta) \]

\[ N(\theta, \varepsilon) = \text{Im} \left( \frac{\varepsilon^R \frac{\Delta(\theta)^2}{D^R}}{\varepsilon^R D^R} \right) \]

\[ \varepsilon^R(\theta, \varepsilon) = \varepsilon + i\gamma + (e/c)v_f.A(R) \]

**Large tunneling cone**

If \( D(\theta) = 1 \),

\( \phi = 180^\circ \)

\( \phi = 50^\circ \)

**Small tunneling cone,**

\( \phi = 20^\circ \)
Tunneling cone filter: Data and Calculations

Data:
(zirconia-based junctions)

Calculations:
(110) YBCO Thin Film

AFM: RMS roughness ~few nm over ~.5 µ

Some ~atomically-flat regions (red arrows)
In-plane Quasi-particle Tunneling into $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8$ Single Crystals

NEW junction Fabrication Technique:
1. Cut and Polish to RMS Roughness $\sim 80 \text{ Å}$ (AFM)
   $\Rightarrow$ **No Faceting and Atomic Scale Damage**
2. Evaporation of ultra-thin (1nm) $\text{CaF}_2$ insulating layer
3. Ag counter electrodes
BSCCO Single Crystals: in-plane Crystallographic Orientation Dep.

$T = 4.2 \text{ K}$

$G \text{(mS)}$

$V \text{(mV)}$

BSCCO Single Crystals: Magnetic Field Dependence
Magnitude and orientation:

Anisotropic QP Transport & Hysteresis

Suppression of ZBCP with applied field, field orientation dependent.

DoS spectral weight conserved within 5%

No splitting observed!
II. The IBS effect on ABS

One Idea: Samokhin and Walker, PRB, 2001: Showed that a ZBCP due to IBS does not split in a field, only broadens (like the grain-boundary, ramp and single-crystal junctions). [e.g., IBS swamp IBS, and the IBS are localized around the scattering centers]

But: This model requires the IBS to swamp the ABS. The spectral weight of the IBS is much lower than that of the ABS, and with so many impurities, phase coherence (d-wave sc) would be lost.

And: If the IBS dominates the ABS in the ZBCP, there should be no orientation dependence!
Preliminary Model

ABS plus some surface disorder creating some IBS (impurity bound state), near the ABS, both spatially and in energy, cause ABS to be Homogeneously Broadened.

Cartoon:

Homogeneously broadened peak will split.
Add some IBS near interface:

**ABS** (surface-induced)

**IBS** (impurity-induced)

**IBS act as scattering centers**
to scatter **ABS** along different trajectories:

**ZBCP is now an inhomogeneously-broadened**
band of quasiparticles:

**Cartoon:**

Inhomogeneously broadened peak will not split,
will only suppress and broaden.
Outstanding questions in high-temperature and unconventional superconductivity:

Finding the mechanism for superconductivity.

Finding reliable ways to measure if a superconductor is unconventional, and the symmetry of its pairing state.

Understanding the role of disorder, including interfaces. Conventional superconductors are typically metals or alloys, but the unconventional superconductors tend to be compounds. Therefore, they are more fragile, i.e., are more sensitive to structural disorder. In unconventional superconductors, even a small change in physical structure can cause a profound effect on their electronic structure, so this remains an important question, both for the basic understanding of the physical state, and for applications.

Finding reliable ways to measure if time-reversal symmetry is broken. This is a challenging, because the magnetism can occur in a very small fraction of the superconductor, and is buried within the superconducting state.
Planar Tunneling Spectroscopy vs. STM:
(measurements compliment each other)

Advantages:
I. Can obtain high momentum resolution (tunneling cone)
II. Stable configuration:
   can easily study as a function of field, temperature, area and, most important, reproducibility.

Drawbacks:
I. Damage to surface during junction fabrication
II. Low spatial resolution