STM on High-Tc Superconductors
This talk:

- Basic STM on cuprates: inhomogeneity, qp interference, signs of d-wave
- New technique: Watching superconductivity develop on the atomic scale
- Precise measurements of electron-boson coupling on the atomic scale
- Connection between normal and superconducting states
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Pairing is local & occurs above $T_c$ (OP & OV samples)
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Electron-boson coupling?

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Electron-boson coupling?

Superconductor mimics normal state
# Families of Hole-doped Cuprate Superconductors

<table>
<thead>
<tr>
<th>Holepan Family</th>
<th>Bi Family</th>
<th>(a)</th>
<th>(b)</th>
<th>(c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pb Family</td>
<td>1L Ti Family</td>
<td></td>
<td></td>
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<tr>
<td>La Family</td>
<td>2L Family</td>
<td></td>
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<tr>
<td>YBCO Family</td>
<td>Hg Family</td>
<td></td>
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</table>

<table>
<thead>
<tr>
<th>Family</th>
<th>$T_c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ca$_2$Na$_2$CuO$_2$Cl$_2$</td>
<td>26</td>
</tr>
<tr>
<td>Pb$_2$Sr$_2$La$_2$Cu$_4$O$_8$</td>
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<tr>
<td>La$_2$MgCuO$_4$</td>
<td>39</td>
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<tr>
<td>Bi$_2$Sr$_2$La$_2$CuO$_8$</td>
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<tr>
<td>TIBa$_2$La$_2$CuO$_8$</td>
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<tr>
<td>Sr$_2$CuO$<em>2$F$</em>{2+x}$</td>
<td>40</td>
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<tr>
<td>La$_2$CuO$_4$</td>
<td>45</td>
</tr>
<tr>
<td>Tl$_2$Ba$<em>2$CuO$</em>{6+\delta}$</td>
<td>93</td>
</tr>
<tr>
<td>HgBa$<em>2$CuO$</em>{4+\delta}$</td>
<td>98</td>
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<tbody>
<tr>
<td>La$_2$Sr$_2$Ca$_4$Cu$_2$O$_8$</td>
<td>60</td>
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<tr>
<td>(La$<em>{1.5}$Ca$</em>{0.5}$)(Ba$<em>{1.75}$Ca$</em>{0.25}$)$_2$Sr$_2$Cu$_2$O$_y$</td>
<td>80</td>
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<tr>
<td>Bi$_2$Sr$_2$Ca$_4$Cu$<em>2$O$</em>{8+y}$</td>
<td>90</td>
</tr>
<tr>
<td>Pb$<em>2$Sr$<em>2$Y$</em>{1.4}$Ca$</em>{6.6}$Cu$<em>8$O$</em>{20.8}$</td>
<td>80</td>
</tr>
<tr>
<td>Y$<em>{1.4}$Ca$</em>{6.6}$Ba$_2$Cu$<em>8$O$</em>{20.8}$</td>
<td>90</td>
</tr>
<tr>
<td>Bi$_2$Sr$_2$Ca$<em>4$Y$</em>{1.4}$Cu$<em>2$O$</em>{8+y}$</td>
<td>96</td>
</tr>
<tr>
<td>YBa$_2$Cu$<em>3$O$</em>{7+y}$</td>
<td>93</td>
</tr>
<tr>
<td>TlBa$_2$CaCu$<em>2$O$</em>{7.6}$</td>
<td>110</td>
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<tr>
<td>TIBa$_2$Ca$_2$Cu$<em>2$O$</em>{13+\delta}$</td>
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<tr>
<td>TiBa$_2$Ca$_2$Cu$<em>2$O$</em>{13+\delta}$</td>
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<tr>
<td>Tl$_2$Ba$_2$Ca$_2$Cu$<em>2$O$</em>{10+\delta}$</td>
<td>125</td>
</tr>
<tr>
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*Highest $T_c \sim 135$K*

From Esaki et al 2004
Phase Diagram of Hole Doped Cuprates

Hole Density in CuO$_2$ Plane

Temperature

Anti-Ferromagnetism

Superconductor

Normal Metal ?

5% 12.5% 16% 30%
Phase Diagram of Hole Doped Cuprates

- Temperature
- Superconductor
- Normal Metal?
- Anti-Ferromagnetism

Hole Density in CuO$_2$ Plane
- 5%
- 12.5%
- 16%
- 30%

Disordered Magnetism & Stripes
Phase Diagram of Hole Doped Cuprates

- Temperature
- Anti-Ferromagnetism

Stripes: Spin/Charge Ordering

Hole Density in CuO$_2$ Plane
- 5%
- 12.5%
- 16%
- 30%

Superconductor

Normal Metal?
Phase Diagram of Hole Doped Cuprates

- Temperature
- Hole Density in CuO$_2$ Plane

- Pseudogap “Phase”
- Superconductor
- Anti-Ferromagnetism
- Disordered Magnetism & Stripes
- Normal Metal ?
Phase Diagram of Hole Doped Cuprates

- Normal Metal ?
- Anti-Ferromagnetism
- Pseudogap “Phase”
- Fluctuating Superconductor
- Disordered Magnetism & Stripes
- Superconductor

Hole Density in CuO$_2$ Plane:
- 5%
- 12.5%
- 16%
- 30%
What have been accomplished after 20 years?

- Superconducting state involves Cooper pairs
- The pair wavefunction has d-wave symmetry, change of sign and nodes
- Demonstrated by phase sensitive & angle resolved photoemission experiments
What have been accomplished after 20 years?

- The Fermi surface on the overdoped side of the phase diagram
- Large hole barrels for hole doped cuprates on overdoped side
- Strange partially gapped Fermi surface in underdoped side
- Nature of underdoped samples FS still highly debated

T>Tc Overdoped

T>Tc underdoped pseudogap state


Key Questions I:

- What is the correct microscopic Hamiltonian?

Reduce to one band Hubbard Model?

• Pairing Mechanism?

RVB Approach:

\[
\begin{align*}
\left| \uparrow_{r} \downarrow_{r'} \right> - \left| \downarrow_{r} \uparrow_{r'} \right> \\
\sqrt{5}
\end{align*}
\]

• nearest neighbor d-wave pairing

Anderson (1987); Kotliar & Lu (1988); others
Numerical Calculations of the Hubbard Model: n.n. d-wave pairing
- Somehow a retarded interaction can be constructed
- Perhaps at sufficiently high doping close to normal metal
- A Pairing glue? Even in the Hubbard model
- Example: Spin Fluctuations
Somehow a retarded interaction can be constructed
Perhaps at sufficiently high doping close to normal metal
A Pairing glue? Even in the Hubbard model
Example: Spin Fluctuations
Anderson-Scalapino Debate

Aspen 2007

See Science Letters 2007
Phil: No glue required!
Doug: A separation of energy scales as in BCS may be still possible
Key Questions II:

- When do pairs form? At Tc or above? $\Psi = |\Delta| \exp(i\Phi)$
- Pseudogap? What is it?
- Due to competing orders or pairing?
- Tc occurs due to phase coherence? paired above?
Key Questions II:

• When do pairs form? At Tc or above?  \( \Psi = |\Delta| \exp(i\Phi) \)
• Pseudogap? What is it?
• Due to competing orders or pairing?
• Tc occurs due to phase coherence? paired above?

Experiment by Wang, Li, Ong and coworkers 2002
From PA Lee ‘00
Key Questions II:

- When do pairs form? At $T_c$ or above? $\Psi = |\Delta| \exp(i\Phi)$
- Pseudogap? What is it?
- Due to competing orders or pairing?
- $T_c$ occurs due to phase coherence? paired above?

Enhanced Diamagnetism Exp
Li, Wang, & Ong et al.
Gaiver Tunneling in the Cuprates:

Due to d-wave nature of the order parameter very sensitive to interface disorder.
Gaiver Tunneling in the Cuprates:

Due to d-wave nature of the order parameter very sensitive to interface disorder.

\[
\Delta_d = 40 \text{ meV} \quad \Gamma = 6 \text{ meV}
\]

\[d\text{-wave (}\Gamma=6\text{meV)}\]
Probing Electronic States With the STM

- **Imaging:**

  Tip trajectory at constant current is an image of the contours of constant electron density

  \[
  I(r, V) \propto \int \frac{E_{F+v}}{E_F} |\Psi(r, E)|^2 T(E) \, dE
  \]

- **Spectroscopy:**

  \[
  \frac{dI}{dV}(V) \propto \rho(r, V)
  \]

  Local density of state of the sample as a function of position & energy
High-Tc Material System: $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$

At Optimal Doping for this system: $T_c \sim 93K$
High-Tc Material System: $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$

At Optimal Doping for this system: $T_c \sim 93K$
Cleaved $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+d}$
Superconducting State Tunneling Spectra for an overdoped sample ($x=0.225$) $T_c=65$K sample
Superconducting State Tunneling Spectra for an overdoped sample (x=0.225) Tc=65K sample

\[ dI/dV \text{ [pS]} \]

\[ \text{Voltage [meV]} \]

\[ \Delta_d = 40 \text{ meV} \]

\[ \Gamma = 6 \text{ meV} \]

\[ \text{DOS [arb]} \]
Spatial Variation of the tunneling spectra in superconducting state (overdoped doping Tc=65K, T=40K)
Previously reports of inhomogeneous gaps on 2212 has been made by Cren, Pan, Davis, Kapitulnik.

Inhomogeneous Gaps

overdoped sample

T < Tc (T = 30K, Tc = 68K)
Inhomogeneous Gaps

300 Å x 300 Å

Δ(mV)

18mV

38mV

overdoped sample

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Spatial Structure of Electronic States
&
Quantum Interference for a d-wave Superconductor
Optimally doped Sample Tc=93K

Conductance Maps Below Tc

Homogeneity of Nodal QP

25pS

300pS

520 Å x 520 Å

dI/dV [pS]

Voltage [V]

Optimally doped Sample Tc=93K
Optimally doped Sample $T_c=93\text{K}$

Conductance Maps Below $T_c$

Homogeneity of Nodal QP

$520 \text{Å} \times 520 \text{Å}$
Fourier analysis of the modulation in the local density of states of the superconducting state ($T=T_c/2$)
Fourier analysis of the modulation in the local density of states of the superconducting state \( (T=T_c/2) \)
Quantum Interference in the Superconducting State of a Cuprate Superconductor

Scattering between equal energy counters.

The belief is that scattering is dominated by points with large density of states

\[ n(E) = \int_{E(k)=E} \frac{1}{\nabla_k E(k)} \, dk \]

Quantum Interference in the Superconducting State of a Cuprate Superconductor

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$\mathbf{x}$

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\[ n(E) = \frac{1}{\sqrt{\operatorname{det} \nabla_k E(k)}} dk \]

Quantum Interference in the Superconducting State of a Cuprate Superconductor

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Quantum Interference in the Superconducting State of a Cuprate Superconductor

Scattering between equal energy counters.

The belief is that scattering is dominated by points with large density of states.

\[
\frac{1}{\nabla_k E(k)} \frac{1}{E(k) - E} dk
\]

Quantum Interference in the Superconducting State of a Cuprate Superconductor

Scattering between equal energy counters.

The belief is that scattering is dominated by points with large density of states.

$n(E) = \int_{E(k)=E} \frac{1}{\nabla_k E(k)} \, dk$

Lower temperatures measurements show more spots

Energy (meV)
Local Signature of d-wave Pairing
Nanoscale Signatures of d-wave Pairing in the Cuprates

- Changing Direction in a d-wave: $\pi$-phase shift

$\Delta(k)$

Momentum Space Variation of Gap

1D model:
Zero Energy Solution

- Andreev surface bound state

- At defects structures

Hu '94, Tanaka et al. '95, Covington et al. '97, ....

Chen et al. '96, Adagideli, et al. PRL’99 (UIUC)
Andreev Bound State at a Surface of a $d$-wave Superconductor

110 Edge at 45° relative to CuO

One dimensional Andreev Bound State appear at $E = E_F$

C. Hu, PRL 72, 1526 (1994)
Y. Tanaka et al. (1995)
M. Covington et al., PRL 79, 277 (1997)
D. Morr and E. Demler, cond-mat/0010460
One Dimensional Andreev Bound State at the Edge of a \textit{d-wave} 

\[ T\ll T_c \]

100Å x 100Å
One Dimensional Andreev Bound State at the Edge of a \textit{d-wave}

\begin{align*}
T \ll T_c \\
100\text{Å} \times 100\text{Å}
\end{align*}

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{image.png}
\caption{BiO Plane}
\end{figure}

\textbf{1D model: Zero Energy Solution}

\begin{align*}
+\Delta \\
-\Delta
\end{align*}

S. Misra \textit{et al.} PRB RC 2002

Similar zero-dimensional phenomena near unitary scatters
One Dimensional Andreev Bound State at the Edge of a d-wave

Spectra to the step

100Å x 100Å

T<<Tc

1D model: Zero Energy Solution

S. Misra et al. PRB RC 2002

Similar zero-dimensional phenomena near unitary scatters
One Dimensional Andreev Bound State at the Edge of a \textit{d-wave}.

\textbf{Spectra to the step}

\begin{itemize}
\item $T << T_c$
\item $100\text{Å} \times 100\text{Å}$
\end{itemize}

\textbf{1D model: Zero Energy Solution}

\begin{itemize}
\item $+\Delta$
\item $-\Delta$
\end{itemize}

S. Misra \textit{et al.} PRB RC 2002

Similar zero-dimensional phenomena near unitary scatterers.
Impurity Induced Resonance in a d-wave Superconductor

Applying Shiba’s Work to d-wave:
Balatsky et al. 1995, Salkola et al. 1996,
Flatte and Byers ‘98

- Energy

\[ \Omega_0 \approx \frac{\Delta_0}{2UN_F(\ln 8UN_F)} \]

- Width

\[ \Gamma \approx \frac{\pi \Omega_0}{2(\ln 8UN_F)} \]

- Strong scattering limit:

Simple Picture: Without e-h asymmetry
Resonance induced by nonmagnetic impurity

See Review by Balatsky et al.
arXiv:cond-mat/0409474
Defect Scattering on the BiO Surface:

Native Defects
A. Yazdani et al. PRL 1999

Similar data by Hudson et al. Science 1999

Au defects on BiO

36Å x 36Å

A. Yazdani et al. PRL 1999
**Effect of Zn-impurity on the Superconducting State**


- **Spectroscopy on/off the Zn dopent**
  - Zn replaces the Cu atoms and kills $T_c$.
  - **Missing Cu**: At Zn site NMR experiments (normal state) see a local magnetic moment
  - **Various models**: Resonant scattering, Kondo scattering, ...

Map of DOS at $V=0$ (Fermi level)
Ni Impurities as a marker for local superconductivity

- Ni produces a low energy Shiba state--with d-wave symmetry (Hudson et al. 2001)
- Bound states are spatially asymmetric with respect of electrons and hole excitations

Hudson et al., Nature 411, 920 (2001)
Questions:

- When do pairs form?
- Are there bosonic excitations that couple to electrons?
- What controls the pairing strength?
Inhomogeneous Gaps

Previously reports of inhomogeneous gaps on 2212 has been made by Cren, Pan, Davis, Kapitulnik.
Inhomogeneous Gaps

300 Å x 300 Å

\[ \Delta(mV) \]

18mV

38mV

overdoped sample

\[ T < T_c \ (T=30K, T_c=68K) \]

Previously reports of inhomogeneous gaps on 2212 has been made by Cren, Pan, Davis, Kapitulnik.
What happens with increasing temperature?

- Pseudogap “Phase”
- Fluctuating Superconductor
- Superconductor
- Ant-Ferromagnetic
- Disordered Magnetism & Stripes
- Normal Metal?
Variable Temperature UHV STM:
Can be used to track a single atomic site with T

- Thermal compensation
- Compact design
- Result:
- Extremely low drift at high temperatures

(8K<T<350K)
Lattice-Tracking Spectroscopy

Overdoped Sample
Spot #1

Avoiding Material Inhomogeneity with LTS

Tc = 68K
Lattice-Tracking Spectroscopy

Overdoped Sample Spot #1

Avoiding Material Inhomogeneity with LTS

Tc = 68K

Voltage [meV]

dI/dV [pS]
Lattice-Tracking Spectroscopy

Overdoped Sample
Spot #1

Avoiding Material Inhomogeneity with LTS

T_c=68 K
Avoiding Material Inhomogeneity with LTS

Lattice-Tracking Spectroscopy

Tc=68K

Overdoped Sample
Spot #1

$\frac{dI}{dV}$ [pS]
Voltage [meV]

Tc=68K
Lattice-Tracking Spectroscopy

Overdoped Sample
Spot #1

Avoiding Material Inhomogeneity with LTS

Tc=68K
Lattice-Tracking Spectroscopy

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T_c=68K
Lattice-Tracking Spectroscopy

Overdoped Sample
Spot #1

Avoiding Material Inhomogeneity with LTS

Tc=68K
Inhomogeneous Gaps:

300 Å x 300 Å

Δ(mV) 18mV 38mV

OV68

Spot #1
Inhomogeneous Gaps:

300 Å x 300 Å

Δ(mV)

18mV  38mV

Probability [%]

Spot #1

Spot #2

Gap [mV]

OV68
Lattice-Tracking Spectroscopy:

Overdoped Sample
Spot # 2

$T_c=68\text{K}$
Lattice-Tracking Spectroscopy:

Overdoped Sample
Spot # 2

Tc = 68K
Lattice-Tracking Spectroscopy:

Overdoped Sample
Spot # 2

Tc=68K
Lattice-Tracking Spectroscopy:

Overdoped Sample
Spot # 2

$T_c = 68K$

$dI/dV$ [pS]
Voltage [meV]

$T_c = 68K$
Lattice-Tracking Spectroscopy:

Overdoped Sample
Spot # 2

\[ \frac{dI}{dV} \text{[pS]} \]

Voltage [meV]

\[ T_c=68K \]
Lattice-Tracking Spectroscopy:

Overdoped Sample
Spot # 2

Tc=68K
Lattice-Tracking Spectroscopy:

Overdoped Sample
Spot # 2

Tc=68K
Non-uniform closing of the gaps (T=70K) for an overdoped sample (Tc=65K)
Non-uniform closing of the gaps 
(T=70K) for an overdoped sample (Tc=65K)

Experimental Procedure:
\[ \Delta = 0 \text{ when } \frac{dI}{dV}(0) \geq \frac{dI}{dV}(\text{all } V > 0) \]
Local d-wave Pairing Gap Collapse

Background: Tunneling Matrix Element
Incoherent tunneling processes

Overdoped Sample
Spot #1

Avoiding Material Inhomogeneity with LTS

Tc=68K
Conductance Ratio: $R = \frac{[dI/dV]_s}{[dI/dV]_n}$

For the case that the “normal state” is T-independent

Overdoped Sample
Spot #1

$T_c = 68\,\text{K}$
Conductance Ratio: \( R = \frac{[dI/dV]_S}{[dI/dV]_N} \)

For the case that the normal state is T-independent

Overdoped Sample
Spot #2

\( T_c = 68K \)
Fitting Conductance Ratio with a Local d-wave Model:

\[
\frac{N_S(r,V,T)}{N_N(r,V)} = \frac{1}{\pi} \int dE \frac{df(E+V,T)}{dE} \int_0^\infty d\theta \text{Re} \frac{E - i\Gamma(r,T)}{\sqrt{(E - i\Gamma(r,T))^2 - \Delta(r,T)^2 \cos^2 2\theta}}
\]

\[\Delta(r,T)\] - local d-wave gap

\[\Gamma(r,T)\] - local inverse QP lifetime

Different Spots on the OV68 at T=30K
Fitting Conductance Ratio with a Local $d$-wave Model:

$$\frac{N_S(r,V,T)}{N_N(r,V)} = \frac{1}{\pi} \int dE \frac{d\Gamma(E+V,T)}{dE} \int d\theta \text{Re} \frac{E-i\Gamma(r,T)}{\sqrt{(E-i\Gamma(r,T))^2 - \Delta(r,T)^2 \cos^2 2\theta}}$$

$\Delta(r,T)$ - local $d$-wave gap

$\Gamma(r,T)$ - local inverse QP lifetime

Different Spots on the OV68 at $T=30K$
Fitting Conductance Ratio with a Local d-wave Model:

\[
\frac{N_S(r,V,T)}{N_N(r,V)} = \frac{1}{\pi} \int dE \frac{df(E+V,T)}{dE} \int d\theta \text{Re} \frac{E - i\Gamma(r,T)}{\sqrt{(E - i\Gamma(r,T))^2 - \Delta(r,T)^2 \cos^2 2\theta}}
\]

- \(\Delta(r,T)\) - local d-wave gap
- \(\Gamma(r,T)\) - local inverse QP lifetime

Different Spots on the OV68 at T=30K
Fitting Conductance Ratio with a Local d-wave Model:

\[
\frac{N_s(r,V,T)}{N_N(r,V)} = \frac{1}{\pi} \int dE \frac{df(E + V,T)}{dE} \int d\theta \text{Re} \frac{E - i\Gamma(r,T)}{\sqrt{(E - i\Gamma(r,T))^2 - \Delta(r,T)^2 \cos^2 2\theta}}
\]

\(\Delta(r,T)\) - local d-wave gap

\(\Gamma(r,T)\) - local inverse QP lifetime

Different Spots on the OV68 at T=30K

Excellent fit at low E
Fitting the T-dependence of the Conductance Ratio:

\[
\frac{N_s(r,V,T)}{N_N(r,V)} = \frac{1}{\pi} \int dE \frac{df(E+V,T)}{dE} \int_0^{\pi} d\theta \text{Re} \frac{E-i\Gamma(r,T)}{\sqrt{(E-i\Gamma(r,T))^2 - \Delta(r,T)^2 \cos^2 2\theta}}
\]

\(\Delta(r,T)\) - local d-wave gap \hspace{1cm} \(\Gamma(r,T)\) - local inverse QP lifetime
Extract the local d-wave Pairing Gap
Extract the local d-wave Pairing Gap

Gap size (mV) vs Temperature (K)

“Tp’s”
Extract the local d-wave Pairing Gap

Gap size (mV) vs. Temperature (K)

"Tp’s"
Evolution of gaps in the overdoped regime

Temperature (K)

Doping

Gap Coverage (%)
Evolution of gaps in the overdoped regime

![Graph showing the evolution of gaps in the overdoped regime with temperature and doping. The graph includes a curve labeled $T_c$ and a color-coded area indicating gap coverage.](image-url)
Slightly overdoped Sample $T_c = 83K$

Gaps get large with reduced doping
Evolution of gaps in the overdoped regime

![Graph showing temperature (K) vs. doping, with a color scale indicating gap coverage (%).]
Evolution of gaps in the overdoped regime

\[ T_c \]

Temperature (K)

Doping

Gap Coverage (%)
Optimally doped Sample $T_c=93K$
Local Pairing Gap Detected Above Tc

The graph shows the relationship between temperature (K) and doping, with the gap coverage (%) indicated by the color scale. The critical temperature (Tc) is marked on the graph, and the data points represent experimental measurements.
Local Pairing Gap Detected Above $T_c$

![Graph showing the relationship between temperature and doping with a color-coded gap coverage percentage.](image-url)
Thermodynamic transitions in inhomogeneous $d$-wave superconductors

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FIG. 2: (Color online) OP maps, parameters from Fig. 1(d): $T = 0.18t$ (a), $T = 0.20t$ (b), $T = 0.22t$ (c), and $T = 0.24t$ (d).
Is there a relation between $T_p$ and $\Delta$?

- Smaller $\Delta$ will vanish first
- $T_p \propto \Delta$?
- Gap distribution is also $T_p$ distribution
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Integral of Gap Histogram = Percentage of Ungaped Regions
Relation between $T_p$ and $\Delta$?

OV83
Relation between $T_p$ and $\Delta$?

$$\frac{2\Delta}{k_B T_p} = 7.9 \pm 0.2$$
Relation between $T_p$ and $\Delta$?

\[
\frac{2\Delta}{k_B T_p} = 7.9 \pm 0.2
\]

- The ratio is much higher than BCS weak coupling limit (~4 for d-wave).
- Optimal/Overdoped samples appear to have only one energy scale, the pairing gap
Average Relation between $T_p$ and $\Delta$

$$\frac{2\Delta}{k_B T_p} = 8.0 \pm 0.5$$
Average Relation between $T_p$ and $\Delta$

$\frac{2\Delta}{k_B T_p} = 8.0 \pm 0.5$

~ 1,000,000 Independent Measurements
Compare to other experiments?

Gomes, Pasupathy, Pushp, Ono, Ando, Yazdani  Nature 447, 569 (2007)
Compare to other experiments?

![Graph showing temperature (K) vs. doping with Tc and Tp(max) annotations.]

Compare to other experiments?

![Graph showing doping and temperature with labels and data points]

What happens on the dark side?

Disordered Magnetism & Stripes
Underdoped Samples: Unusual shaped spectra

\[ T < T_c \]
Underdoped Samples: Unusual shaped spectra

T<T_c
Underdoped Samples: Static Electronic Modualations

FFT of conductance maps for $T<T_c$
Underdoped Samples: Static Electronic Modulations

FFT of conductance maps for $T < T_c$
Underdoped Samples: Static Electronic Modulations

FFT of conductance maps for $T < T_c$

Static Modulations with close to 4a spacing
Underdoped Samples: Static Electronic Modulations

Local Ordering in the Pseudogap State of the High-$T_c$ Superconductor Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$

Michael Vershinin, Shashank Misra, S. Ono, Y. Abe, Yoichi Ando, Ali Yazdani


FFT of conductance maps

Energy-resolved conductance maps at $T>T_c$

Static Patterns appear for $E<P_G$

FFT of conductance maps
Underdoped Samples: Static Electronic Modualations

**Local Ordering in the Pseudogap State of the High-$T_c$ Superconductor Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$**

Michael Vershinin,$^1$ Shashank Misra,$^1$ S. Ono,$^2$ Y. Abe,$^2\dagger$ Yoichi Ando,$^2$ Ali Yazdani$^{1,\S}$

*Science 303, 1995 (2004)*

Energy-resolved conductance maps at $T>T_c$

Static Patterns appear for $E<PG$

FFT of conductance maps
Origin of Static Patterns in the Pseudogap State

- Disordered Stripes?
- Nesting of FS?
- AF zone boundary?
- Valance bond solid?
- Regardless: correlate with PG

Local Pairing is Pseudogap Physics above Optimal doping

\[ T_p(\text{max}) \sim T^* \]

Questions:

- When do pairs form? *From locally over a range of temperatures above $T_c$.*
- Are there bosonic excitations that couple to electrons?
- What controls the pairing strength?
“Electron-Boson coupling” Features:

- Data shows a dip below “weak-coupling” d-wave
- Definite signature of coupling to some sort of a boson

Electron-Phonon coupling in Pb

Overdoped Sample
T=30K
“Electron-Boson coupling” Features:

- Data shows a dip below “weak-coupling” d-wave
- Definite signature of coupling to some sort of a boson

Systematic Deviation from local d-wave model

Electron-Phonon coupling in Pb

Overdoped Sample

T=30K
Angle Resolved Photoemission Spectroscopy & Electron-Boson Coupling

Data from D. Dessau (U of Col.) seen by all photoemission groups
Angle Resolved Photoemission Spectroscopy & Electron-Boson Coupling

Data from D. Dessau (U of Col.) seen by all photoemission groups
STM/ARPES Spectra features & the “Glue”

- Bosonic Battles: magnetic or lattice; Relevant to pairing or not?
STM/ARPES Spectra features & the “Glue”

• Bosonic Battles: magnetic or lattice; Relevant to pairing or not?
STM/ARPES Spectra features & the “Glue”

• Bosonic Battles: magnetic or lattice; Relevant to pairing or not?

Evidence for ubiquitous strong electron–phonon coupling in high-temperature superconductors


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Interplay of electron–lattice interactions and superconductivity in Bi$_2$Sr$_2$CaCu$_2$O$_8$+δ


Quantitative test of a microscopic mechanism of high-temperature activity

Hou-Cheng Zhang, Ford University, Stanford, California 94305, USA

Neutron Resonance in the Cuprates and its Effect on Fermi

J. Hwang, T. Timusk & G. D. Gu

and Astronomy, McMaster University, Hamilton, Canada

Brookhaven National Laboratory, Upton, New York

High-transition-temperature superconductivity in the absence of the magnetic-resonance mode

J. P. Carbone

n-doped transition-temperature superconductor

Pengcheng Dai, S. Kunwar, S. Zhou, Shiliang Li, H. Ding, Ziqiang Wang, V. Madhavan

....& many others
What is the relation between bosonic features & the gap?

- Quantitative analysis using the locally measured conductance ratio
- Avoids inelastic tunneling & matrix element effects
- Do they control the gap?
Size of the boson mediate features scale with the gap size in a BCS-Eliashburg superconductors

Dynes and Rowell, PRB 11, 1884 (1975)
Electron-Boson Coupling & the SC Gap

**Lessons From the Past:**

Size of the boson mediate features scale with the gap size in a BCS-Eliashburg superconductors

Dynes and Rowell, PRB 11, 1884 (1975)

Different gaps can be achieved via doping it causes changes to electron-phonon coupling

\[ \Delta = \hbar \omega_c e^{-\frac{1}{\lambda}} \]
Electron-Boson Coupling & the Gaps

$R = \frac{[dI/dV]_S}{[dI/dV]_N}$

Voltage - $\Delta$ [meV]

OV68

Inset: Gap [mV]

Probability [%]
Electron-Boson Coupling & the Gaps

$R = \left[ \frac{dI}{dV} \right]_S / \left[ \frac{dI}{dV} \right]_N$

Voltage - $\Delta$ [meV]
Electron-Boson Coupling & the Gaps

\[ \Delta = \hbar \omega_c e^{-\frac{1}{\lambda}} \]

OV68

shifts features in energy

shifts features in magnitude

R = \frac{[dI/dV]_S}{[dI/dV]_N}

Voltage - \Delta [meV]
Lack of Correlation Between Electron-Boson Coupling & the Gaps!

Pasupathy, Pushp, Gomes, Parker, Gu, Ono, Ando, Yazdani. Science, 320, 196 (2008)
Electron Boson Coupling & Frequency Dependent of the Pairing Interaction:

\[
\frac{N_s(r,V,T)}{N_N(r,V)} = \frac{1}{\pi} \int dE \frac{df(E + V,T)}{dE} \int_0^\pi d\theta \text{Re} \frac{E - i\Gamma(r,T)}{\sqrt{(E - i\Gamma(r,T))^2 - \Delta(r,T)^2 \cos^2 2\theta}}
\]

\( N_s(V)/N_n(V) \) is a function of \( V \) and can be less than 1

Within the model:

- \( \Delta \) must have some \( \omega \) dependence
- \( \Delta(\omega) = \Delta_R(\omega) + i \Delta_I(\omega) \)
- Near dip \( \Delta_I(\omega) \sim 25 \text{mV} \)
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Ns(V)/Nn(V) is a function of V and can be less than 1

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Scalapino (1969)
Electron Boson Coupling & Frequency Dependent of the Pairing Interaction:

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\]

Ns(V)/Nn(V) is a function of V and can be less than 1

**Bottom Line:**

- \(\Delta s\) are equally “affected” by bosons (20-120meV)
- Unlikely “cause” of inhomogeneous \(\Delta s\)
Questions:
- When do pairs form? _Over a range of temperatures above Tc._
- Are there bosonic excitation that couple to electrons? Sure. Unlikely cause the major cause of pairing interaction.
- What controls the pairing strength?
Why does the pairing gap vary spatially?

Pairing Gap Map

\( T = 30K \)

\[ \Delta \text{ (meV)} \]

18 - 38
Why does the pairing gap vary spatially?

Pairing Gap Map

T=30K

Structural Features?

Δ (meV)

18 38
Why does the pairing gap vary spatially?

Pairing Gap Map

Structural Features?  Defects/Dopants?

Δ (meV)

18  38

T=30K
What about normal state background?

Different Locations for OV68 @ 100K

Voltage [meV]
What can the “Normal State” Tell us?

Gap Map

$\Delta (\text{meV})$

$T=30K$

300 Å x 300 Å

OV68
What can the “Normal State” Tell us?

Gap Map

T=30K

300 Å x 300 Å

Δ (meV)

18

38

dI/dV Map at E_F

T=93K

300 Å x 300 Å

dl/dV (pS)

160

290
What can the “Normal State” Tell us?

Gap Map

300 Å x 300 Å

Δ (meV)

T=30K

dl/dV Map at E_F

300 Å x 300 Å

T=93K

dl/dV (pS)
What can the “Normal State” Tell us?

Normal State & Gap Maps are anticorrelated!
Strong Anti-Correlation between “Normal” and SC states

Length scale of gap inhomogeneity is set by normal state
“Normal State” Spectra Foreshadow the Gaps

Systematic correlation between shape & eventual gaps

OV68@ 100K

Pasupathy, Pushp, Gomes, Parker, Gu, Ono, Ando, Yazdani  Science, 320, 196 (2008)
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“Normal State” Spectra
Reference by Low-T Gaps

Systematic correlation
between shape &
eventual gaps

OV68@ 100K
“Normal State” Spectra
Reference by Low-T Gaps

Systematic correlation between shape & eventual gaps

Zero Bias Trend
“Normal State” Spectra Reference by Low-T Gaps

Systematic correlation between shape & eventual gaps

Hump Energy Trend

Zero Bias Trend

OV68@ 100K
Spectra Asymmetry & Mott Physics

At optimal doping: 16% doped

Adding electrons hard
Removing electrons easy
Origin of “Hump” in the so-called “Normal Metal”??

- Mott Physics?
- Projected schemes: asymmetric e-h excitation
- Even a “hump”
Conclusions

- Pairing is local and occurs above $T_c$

- Electron-boson coupling unlikely cause of the inhomogeneous local pairing

- Electron-hole asymmetric excitations of the normal state determine both magnitude and variation of pairing at low $T$