Nodal-antinodal quasiparticle anisotropy reversal in the overdoped high-Tc cuprates

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ARPES on $\text{Tl}_2\text{Ba}_2\text{CuO}_{6+\delta}$: Collaborators

- **ARPES at UBC:**

- **Band Structure Calculations:**
  - Ilya Elfimov

- **Samples:**
  - $\text{Tl}_2\text{Ba}_2\text{CuO}_{6+\delta}$
    - D. Peets, Ruixing Liang, D.A. Bonn, W.N. Hardy

- **ARPES Experiments:**
  - Swiss Light Source – SIS Beamline
    - S. Chiuzbaian, M. Falub, M. Shi, L. Patthey
High-Temperature Superconductors

A. Mackenzie et al., PRB 53, 5848 (1996)
Why $\text{Tl}_2\text{Ba}_2\text{CuO}_{6+\delta}$?

$\text{Tl}_2\text{Ba}_2\text{CuO}_{6+\delta}$: ideal HTSC material

- Single CuO$_2$ plane material
- Very high transition: $T_c$(opt)=93K
- No additional CuO chains
- No structural distortions
- Low cation disorder (T/O structure)

- $d_{x^2-y^2}$ SC gap (Tsuei et al., Nature 1997)
- $(\pi,\pi)$ resonant mode (He et al., Science 2002)
- FS from AMRO (Hussey et al., Nature 2003)
Orthorhombic vs. Tetragonal Tl$_2$Ba$_2$CuO$_{6+\delta}$

- High-quality single crystals:
  Orthorhombic Tl2201 grown by self-flux method
  D. Peets, Ruixing Liang, D.A. Bonn, W.N. Hardy

Tetragonal  \((a=3.865\text{Å}; c=23.247\text{Å})\)

Orthorhombic  \((a=5.458\text{Å}; b=5.485; c=23.201\text{Å})\)

Peets et al., cond-mat/0609250 (2006)
Swiss Light Source – SIS Beamline

• ARPES Experiments:
  Surface and Interface Spectroscopy Beamline
  S. Chiuzbaian, M. Falub, M. Shi, L. Patthey

• Twin Undulator

• Monochromator
  Energy Range: 10-800 eV
  Polarization: circular/planar

• ARPES
  Detector: SES2002
  $\frac{E}{\Delta E}>10^4$ ; $\Delta k=0.3^\circ$
  Low T: 10-300K
  spot size: 20x20 $\mu$m$^2$

• Spin resolved ARPES
ARPES: The One-Particle Spectral Function


Photoemission intensity: \[ I(k, \omega) = I_0 |M(k, \omega)|^2 f(\omega) A(k, \omega) \]

Single-particle spectral function

\[
A(k, \omega) = -\frac{1}{\pi} \frac{\Sigma''(k, \omega)}{\left[ \omega - \epsilon_k - \Sigma'(k, \omega) \right]^2 + \left[ \Sigma''(k, \omega) \right]^2}
\]

\(\Sigma(k, \omega)\) : the “self-energy” captures the effects of interactions
**TI2201: Low energy electronic structure**

**TI\(^{3+}\):Ba\(^{2+}\):Cu\(^{2+}\):O\(^{2-}\) in ratios 2:2:1:6**

**Charge Transfer Insulator**
- Short TI-O distance
  - CuO band not \(\frac{1}{2}\) filled
- Cu-Tl substitution
  - Additional hole-doping

**TI2201: Optimally Doped SC**

**Graphical Representation**: A graph showing the energy bands with labels for different points (Z, G, X, P, N) and annotations about the TI\(^{3+}\) and the charge transfer insulator properties. References to Elfimov (2004) and Hussey et al., Nature 425, 814 (2004) are mentioned.
TI2201 : ARPES Results
Hole FS volume

63%  
$p=0.26$/Cu

63%  
$p=0.26$/Cu

62%  
$p=0.24$/Cu

Tl2201: Fermi Surface Volume

LDA

\( V_{FS} = 63\% \)

ARPsES

\( T_c = 30\, \text{K} \)

AMRO

\( T_c = 20\, \text{K} \)


**Tight binding FS fit**

\[
\epsilon_k = \mu + \frac{t_1}{2} (\cos k_x + \cos k_y) + t_2 \cos k_x \cos k_y + \frac{t_3}{2} (\cos 2k_x + \cos 2k_y) \\
+ \frac{t_4}{2} (\cos 2k_x \cos k_y + \cos k_x \cos 2k_y) + t_5 \cos 2k_x \cos 2k_y
\]

\( \mu = 0.2438, \ t_1 = -0.725, \ t_2 = 0.302, \ t_3 = 0.0159, \ t_4 = -0.0805, \ t_5 = 0.0034 \)
ARPES on Tl$_2$Ba$_2$CuO$_{6+\delta}$

\[ A(\mathbf{k}, \omega) = -\frac{1}{\pi^2} \frac{\Sigma''(\mathbf{k}, \omega)}{[\omega - \epsilon_k - \Sigma'(\mathbf{k}, \omega)]^2 + [\Sigma''(\mathbf{k}, \omega)]^2} \]
TI2201: Lineshape evolution around FS
TI2201: Lineshape evolution around FS

![Graph showing lineshape evolution and energy spectra](image)
TL2201: Lineshape evolution around FS
TL2201: Lineshape evolution around FS

- Diagram showing energy levels and binding energy
- Inset with angles and energy levels
- Spectral weight with energy levels at 550 meV, 200 meV, and 30 meV
TI2201: Lineshape evolution around FS
FS and Pseudogap in Underdoped Cuprates

ARPES on Ca$_{2-x}$Na$_x$CuO$_2$Cl$_2$

Nodal-Antinodal Anisotropy in the Cuprates

Quasiparticle anisotropy reversal

Across optimal doping

Platé, Mottershead, Damascelli et al., PRL 95, 077001 (2005)
Peets, Mottershead, Damascelli et al., NJP 9, 28 (2007)
$\text{Tl}_2\text{Ba}_2\text{CuO}_{6+\delta}$: ARPES Results

Overdoped-63K; $T_c = \frac{2}{3} \cdot T_{c,\text{max}}$

Overdoped-30K; $T_c = \frac{1}{3} \cdot T_{c,\text{max}}$

![Graphs showing ARPES results for Tl2201-OD63 and Tl2201-OD30 at 63K and 30K. The graphs illustrate the intensity versus binding energy with peaks at $(\pi, 0)$ and $(\pi/2, \pi/2)$ for both temperatures.]
Polar AMRO in overdoped Ti2201 ($T_c = 15$K)

Changing $B$

Changing $T$ ($\tau$)

Changing $T$ ($\tau$)

$\omega_c \tau = \frac{eB\tau}{m^*}$

All other parameters unchanged

Ditto

$$\frac{1}{\omega_c \tau} = \frac{1}{\omega_0 \tau_0} (1 + \alpha \cos 4\phi)$$

Courtesy of Nigel Hussey
$$\frac{1}{\omega_0\tau_0} \left(1 + \alpha \cos 4\phi\right) = \frac{1-\alpha}{\omega_0\tau_0} + \frac{2\alpha}{\omega_0\tau_0} \cos^2 2\phi$$

Origin of $T$-linear resistivity and $R_H(T)$ due to additional scattering that is maximal at $(\pi, 0)$ & increases linearly with $T$

Courtesy of Nigel Hussey
TI2201: Anisotropic Electronic Scattering?

Anisotropy reversal:
Are the TI2201 ARPES data consistent with AMRO results in overdoped cuprates?

What does ARPES probe?

\[ \sum_{tot} = \sum_{el,f} + \sum_{el,u} + \sum_{inel} \]

- Resolution broadening
- Residual Kz dispersion
- Impurity scattering
T-dependent Coherent Enhancement at Antinodes

\[ \sum_{tot} = \sum_{el,f} + \sum_{el,u} + \sum_{inel} \]

Small-Angle Elastic Scattering

Unitary Limit beyond Born Appr.

Zhu, Hirschfeld, Scalapino, PRB 2004

Wakabayashi, Rice, Sigrist, PRB 2006
Bi2212: Quasiparticle Interference at High Overdoping

- **Antinodal** (near gap energy) interference signal is dominated by scattering between $(0, \pm p)$ and $(\pm p, 0)$
- Consistent with Van Hove singularity crossing the Fermi surface

- **Nodal** (low energy) quasiparticle interference signals no longer visible
- Consistent with decoherence of nodal states

Slezak and Davis, 2006
Abrupt transition in QP dynamics

Across optimal doping

N. Gedik et al., PRL 95, 117005 (2005)
Many quantities change abruptly beyond $x=0.2$

- **Electronic Specific Heat**  
  (Loram, JPCS 2001)

- **Muon Spin Relaxation**  
  (Panagopoulos, SSC 2003)

- **Low-T Hall Number**  
  (Boebinger, 2006)

- **ARPES: QP lifetime**  
  (Plate, Mottershead, Damascelli, PRL 2005)

- **Optical Conductivity**  
  (Molegraaf, van der Marel, Science, 2002; Gedik, Orenstein, PRL 2005; Ma, Wang, PRB 2006)

- **Scanning Tunneling Microscopy**  
  (Slezak and Davis, 2006)

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Kopp, Ghosal, Chakravarty  
Cond-mat/0606431
ARPES on TI2201: Conclusions

Normal State
Fermi Surface

Quasiparticle
Anisotropy
Reversal

Platé, Mottershead, Damascelli et al., PRL 95, 077001 (2005)
Peets, Mottershead, Damascelli et al., NJP 9, 28 (2007)