Surfing q-space of a high temperature superconductor

Adam Kamiński
Ames Laboratory and Iowa State University

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Outline:

- introduction
- origin of the collective mode
- topology of the Fermi surface
- AutoCorrelated (AC) ARPES
Joong-Mok Park  
Ames Laboratory Spectroscopy Group

James Koll

J. C. Campuzano  
University of Illinois at Chicago, Argonne Nat. Lab.

Utpal Chatterjee

M. R. Norman  
Material Science Division, Argonne National Lab.

S. Rosenkranz

M. Randeria  
Ohio State University

T. Takeuchi  
Nagoya University, Japan

Z. Z. Li  
Universite de Paris-Sud, Orsay, France

H. Raffy

K. Kadowaki  
University of Tsukuba, Tsukuba, Japan
We need:

- binding energy - $E_b$
- initial momentum - $k^i$

\[ E_b = E - hv + W \]
\[ k_{i\parallel}^i = k_{f\parallel}^f = \sqrt{\frac{2mE}{\hbar^2}} \sin \theta \]
\[ k_{i\perp}^i = 0 \text{ for quasi 2D samples} \]
Instrumentation:

Sample → Photoelectrons → Lens → Hemispherical Analyzer
angle resolved mode of the lens:

- 32x improvement of angular resolution
- 2D data acquisition: intensity vs kinetic energy & momentum

developed and perfected by
Bjørn Wannberg
Uppsala University/Gammadata-Scienta
Quality of the vacuum

March 1998

Bi2212 OP 90K Antinode

- 10 min after cleave
- 4 hours after cleave

change of $\Delta = 14$ meV

November 2002

Bi2212 OP90K Antinode

data taken on
- 11/23/02
- 11/30/02

Change of $\Delta < 1$ meV
High precision lab-based ARPES spectrometer

Energy resolution:
~1.3 meV

Angular resolution:
0.1 deg.

UV source:
$10^{13}$ photons/sec.
soon: $\mu$m size beam

Sample positioning:
~1$\mu$m
Typical ARPES data:

$$I = \langle \Psi_i | A \cdot p | \Psi_f \rangle^2 A(k, \omega) f(\omega)$$

ARPES intensity

symmetry of $\Psi$

electronic structure + interactions
Spectral function and self energy

spectral function:

\[ A(k, \omega) = \frac{1}{\pi} \left| \frac{|\Sigma''(k, \omega)|}{\omega - v_f^0(k - k_0) - \Sigma'(k, \omega)} \right|^2 + [\Sigma''(k, \omega)]^2 \]

\[ \Sigma' \] - real part of self energy, \[ \Sigma'' \] - imaginary part of self energy

\[ \Delta k = \frac{\Sigma''(k, \omega)}{v_f^0} \]
dispersion from MDC's

The change of scattering rates obtained from MDC peak dispersion and MDC peak widths are the same

Renormalization effects in the superconducting state - magnetic of phonon origin?

Based on the dispersion, we can conclude that the interaction with the collective mode occurs only in the superconducting state, its energy is constant throughout the Brillouin zone, and its strength increases significantly towards the antinode. These properties are consistent with the resonant mode observed by Inelastic Neutron Scattering (INS) experiments.

**Fermi velocity in the normal state**

**Strength of coupling in the SC state**
EDC's in the superconducting state

Strength of coupling from optics and ARPES

### Score card

Properties of the bosonic mode | compatibility
--- | ---

<table>
<thead>
<tr>
<th></th>
<th>magnetic</th>
<th>phonons</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) isotropic energy $\Delta + \Omega$</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>2) momentum anisotropy</td>
<td>yes</td>
<td>yes, recently</td>
</tr>
<tr>
<td>3) temperature dependence</td>
<td>yes</td>
<td>not obvious</td>
</tr>
<tr>
<td>4) doping dependence</td>
<td>yes</td>
<td>not obvious</td>
</tr>
</tbody>
</table>
Topology of the Fermi surface

(0,0)

(0,π)

(π,π)

(0,-π)

(π,-π)

(π,0)
Time evolution of the Fermi surface of $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$

- Bilayer splitting
- Feng et al. (2001)
- Bonding sheet is hole-like
- Antibonding ??
T=100K
Overdoped sample Tc=80K

Bi2212 OD Tc=80K
T=100K (π,0)

E_{ab} = -0.008 ± 0.0005
E_{bb} = -0.10367 ± 0.0028
Overdoped sample $T_c=65K$

$\text{Bi}2212 \text{ OD } T_c=65K$

$T=100K$ (\pi,0)

$E_{ab} = 0.0019 \pm 0.0001$

$E_{bb} = -0.1049 \pm 0.0007$

Kaminski et al. Submitted
Overdoped sample $T_c=65K$

$k_x=0.9 \pi/a$

$k_x=\pi/a$
Also observed in:

**LSCO**

A. Fujimori et al.,

A. Ino et al.,
PRB **65**, 094504 (2002)

Kaminski et al. Submitted
“Amplitude” of the collective mode from optics and ARPES

The topology of the Fermi surface of Bi2201

(a) $h\nu = 16\text{eV}$

(b) $h\nu = 22\text{eV}$

Takeuchi et al. Submitted
3D Fermi surface in overdoped Bi2201

Takeuchi et al. Submitted
Scattering in traditional STM

Cu on Cu(111)

Ag on Ag(111)

SPECS website
FT STM

J. E. Hoffman et al,

J. E. Hoffman et al,

K. McElroy et al,

L. Capriotti et al,

R. S. Markiewicz et al,
AutoCorrelated (AC) ARPES -
ARPES data and q-space

ARPES intensity map

q-space map

\[ S(q, \omega = \omega_0) = \sum_{k_x, k_y} I(k, \omega) I(k + q, \omega) \]
ARPES intensity maps

E = 8 meV
q-space

\[ E = 8 \text{ meV} \]
K. McElroy et al,
Conclusions:

- all identified properties of the bosonic mode observed in ARPES are consistent with magnetic origin

- the topology of the Fermi surface changes from hole-like to electron-like on the overdoped side around Tc~65K in Bi2212

- a dimensional crossover from 2D to 3D electronic structure occurs within superconducting dome in single layer BSCO

- AutoCorrelated ARPES is a new tool to study scattering processes in solids