Electrons in cuprates: view by ARPES

22 K  77 K  132 K  168 K

220 K  276 K  318 K

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Intro

Occam's razor:

"entities should not be multiplied beyond necessity"

Eq.1:

HTSC = LDA + Self-energy + PG
Outline

I. LDA +

II. Self-energy structure

III. Self-energy origin: ARPES and INS

IV. Pseudo-gap
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    Kordyuk *PRB* 79, 020504(R) (2009)
HTSC = LDA + Self-energy + PG

BSCO (2212)  
YBCO (123)
HTSC = LDA + quasiparticles?
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Borisenko *PRL* 2003
Photon energy – an important tool
Photon energy – an important tool

„Waterfalls“

 photon energy 81 eV

 photon energy 45 eV

 photon energy 64 eV

„Champagne glass“

HTSC = LDA + quasiparticles

$\nu = 27$ eV

Kordyuk *PRL* 2006
Quasiparticles?

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

\[ \Sigma'(\omega) = \omega - \varepsilon(k_m) \]

\[ \Sigma''(\omega) = -v_F W(\omega) \]
Quasiparticles?

Voigt profile = Lorentzian $\otimes$ Gaussian
Quasiparticles?

Evtushinsky PRB 2006
well or not well defined quasiparticles?

\[ \Sigma''(\omega) \ll \omega \]
well or not well defined quasiparticles?

\[ \Sigma''(\omega) - \Sigma''(0) \ll \omega \]

\[ \frac{\Sigma''(\omega) - \Sigma''(0)}{\omega} \ll 1 \]
HTSC = LDA + quasiparticles

\[ \rho_0 = \frac{m^*}{ne^2\tau} \approx \frac{k_F}{ne^2\eta} \frac{\Sigma_{im}}{v_r} \]

Evtushinsky PRB 2006
$\text{HTSC} = \text{LDA} + \text{quasiparticles}$

2 meV

20 meV

$n(x)$ problem

inhomogeneity

localization

PG
Self-energy structure

self-consistency means:

$$\Sigma' = KK \Sigma''$$
Self-energy structure: two channels

Kordyuk PRL 2004; PRL 2006
the only channel which reveals some energy scale is critically doping dependent → spin fluctuations
Self-energy structure: Eliashberg function

\[ G \star \chi = \Sigma \]

Evtushinsky 2007
Self-energy structure

1. Self-energy = CHARGE + MAGNETIC
1. Self-energy = **CHARGE** + **MAGNETIC**

Self-energy structure
1. Self-energy = CHARGE + MAGNETIC

2. MAGNETIC (ω AND k AND T)?
Self-energy origin

ARPES and INS
Story of "fingerprints"

"fingerprints" of the phononic spectrum in tunneling differential conductance by Rowell *PRL* 1963
Eliashberg equations

$$\Delta (\omega) = \frac{1}{Z(\omega)} \int_0^{\omega_e} d\omega' \text{Re} \left\{ \frac{\Delta(\omega')}{(\omega'^2 - \Delta^2(\omega'))^{1/2}} \right\} [K_+(\omega',\omega) - N(0)U_c]$$

$$[1 - Z(\omega)] \omega = \int_0^{\omega_e} d\omega' \text{Re} \left\{ \frac{\omega'}{(\omega'^2 - \Delta^2(\omega'))^{1/2}} \right\} K_-(\omega',\omega)$$

$$K_{\pm}(\omega,\omega') = \sum_{\lambda} \int_0^{\omega_e} d\nu \alpha_{\lambda}^2(\nu) F_\lambda(\nu) \left[ \frac{1}{\omega + \omega + \nu + i\delta} \pm \frac{1}{\omega' - \omega + \nu - i\delta} \right]$$

el-ph coupling constant  phonon DOS

Scalapino PR 1966
What about HTSC?

✓ d-wave gap +
  anisotropic electronic structure +
  anisotropic spectra of phonons
  or magnons

require
  momentum resolved
  experimental techniques: ARPES, INS
Constituents of quasiparticle spectrum

\[ A(k, \omega) \]

- bare electrons
- Green function

\[ G_0(k, \omega) \]

\[ \Sigma(k, \omega) \]

\[ \Delta(k, \omega) \]

- self-energy
- superconducting gap
Constituents of quasiparticle spectrum

bare Green function: \[ G_0(k, \omega) \] from ARPES

self-energy: \[ \Sigma(k, \omega) \] from ARPES

\[ G_0^{-1} + G \star \chi = G^{-1} \]

'bosonic' spectrum: \[ \chi(q, \Omega) \] from INS
Constituents of quasiparticle spectrum

bare Green function: \( G_0(k, \omega) \) from ARPES

self-energy: \( \Sigma(k, \omega) \) from ARPES

\[
G_0^{-1} + G \star G \star G = G^{-1}
\]

itinerant SF: \( \chi(q, \Omega) \) from INS and ARPES
Spin-fluctuations: ARPES and INS

\[ G_0^{-1} + G \star \chi = G^{-1} \]

\[ G_0(k, \omega) \]

\[ \chi(q, \Omega) \]

\[ \Sigma(k, \omega) \]

IFW (ARPES) + Hinkov & Keimer (INS) + Dahm & Scalapino 2006
Spin-fluctuations: ARPES and INS
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Spin-fluctuations: ARPES and INS

Spin-fluctuations: ARPES and INS

Spin-fluctuations: ARPES and INS

\[ V_{\text{eff}}(Q, \Omega) = \frac{3}{2} \bar{U}^2 \chi(Q, \Omega) \]

\[ \bar{U} = 1.59 \text{ eV} \]

\[ \lambda_d = 1.39 \]

\[ T_c = 174 \text{ K} \]

General conclusions

1. Spin-fluctuations well describe one-particle spectra in YBCO.

2. In particular, they solve the kink puzzle.

3. $T_c > 150$ K: spin fluctuations have sufficient strength to mediate high-temperature superconductivity.
Is it itinerant?

\[ \chi = G \star G \]
Is it itinerant?

bare spin susceptibility (Lindhard function):

\[ \chi_0(Q, i\Omega_n) = \frac{1}{\pi^2} \int \sum_m G(k, i\omega_m)G(k + Q, i\omega_m + i\Omega_n) dk \]

dynamic spin susceptibility (RPA):

\[ \chi^{0,e}(Q, \Omega) = \chi^{0,e}_0(Q, \Omega)/\left[1 - J^{0,e}_Q \chi^{0,e}_0(Q, \Omega)\right] \]

effective Hubbard interaction:

\[ J^{0,e}_Q = -J_{||}(\cos Q_x + \cos Q_y) \pm J_{\perp} \]

Inosov PRB 2007
Is it itinerant?

- Figure a) shows a graph with two peaks labeled 'odd (42 meV)' and 'even (55 meV)'.
- Figure b) is a graph with energy in meV and wave vectors in r.l.u.
- Figures c), d), and e) are contour plots with energies of 20 meV, 42 meV, and 60 meV, respectively.
\[ \Sigma(k, \omega) \]
\[ G_0^{-1} + G \star G \star G = G^{-1} \]
\[ \chi(q, \Omega) \]
Pseudo-gap in BSCCO
Non-monotonic pseudo-gap in BSCCO

Kordyuk PRB (2009)
Non-monotonic pseudo-gap in BSCCO

Kordyuk *PRB* (2009)
Non-monotonic pseudo-gap in BSCCO

Kordyuk *PRB* (2009)
Non-monotonic pseudo-gap in BSCCO

Kordyuk *PRB* (2009)

Borisenko *PRL* (2008)
2H-TaSe$_2$ crystal structure, CDW transitions

- 2nd-order transition to an incommensurate CDW at $T_{\text{NIC}} = 122$ K
- 1st-order lock-in transition to a 3x3 commensurate CDW at $T_{\text{ICC}} = 90$ K
Fermi surface: commensurate CDW state

Borisenko *PRL* 2008

Craven & Meyer *PRB* 1977
Pseudogap in 2H-TaSe$_2$ and Tb-BSCCO

![Graphs showing temperature vs. pseudogap for 2H-TaSe$_2$ and Tb-BSCCO](image)

- $T_{IC}$
- $T_{N}$
- $T_{*}$

Fermi surface angle (°) and Leading edge position (meV) are plotted for different temperatures and doped states.
Non-monotonic pseudo-gap in BSCCO

Kordyuk *PRB* (2009)
Pseudo-gap competes with SG

Kondo Nature (2009)
General conclusions

1. HTSC = LDA + PG + Self-energy = QP spectrum
General conclusions

1. HTSC = LDA + PG + Self-energy

2. Self-energy = CHARGE + MAGNETIC
General conclusions

1. HTSC = LDA + PG + Self-energy

2. Self-energy = CHARGE + MAGNETIC + phonons
1. HTSC = LDA + PG + Self-energy = QP spectrum
2. Self-energy = CHARGE + MAGNETIC
3. MAGNETIC = QP spectrum + SF spectrum
General conclusions

1. HTSC = LDA + PG + Self-energy = QP spectrum

2. Self-energy = CHARGE + MAGNETIC

3. MAGNETIC = QP spectrum ★ SF spectrum

\( T_c = 150 \text{ K} \)
General conclusions

1. HTSC = LDA + PG + Self-energy = $\text{QP spectrum}$

2. Self-energy = CHARGE + MAGNETIC

3. MAGNETIC = QP spectrum ★ SF spectrum

4. PG = Electron density modulation =
   = incommensurate xDW ($x = \text{C, D, S...}$)

$T_c = 150 \text{ K}$
Outlook

1. \( x\text{DW in cupates: } x = C, D, S \text{ or ... ?} \)

2. How \( x\text{DW competes with SC?} \)

3. What is PG origin at height \( T \)?

4. How general is DW in 2D?
How general is DW in 2D?

CDW crossovers in dichalcogenides

Charge-orbital ordering in $\text{La}_{0.5}\text{Sr}_{1.5}\text{MnO}_4$

Nesting-driven magnetic ordering in rare earth silicides

($\pi$, $\pi$) electronic order in pnictides

References:
- Borisenko, PRL 2008
- Evtushinsky, PRL 2008
- Inosov, PRL 2009
- Evtushinsky, 2008
- Borisenko, PRL 2008
- Evtushinsky, PRB 2009
- Zabolotnyy, Nature 2009
- Evtushinsky, PRB 2009
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