Phase mixture and pseudogap behavior in the bismuthate high Tc superconductors
Acknowledgments

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Unconventional superconductors

Strongly correlated systems

Transition metal dichalcogenides

Rare earth nickelates

Manganites

Unconventional superconductors

Pseudogap term is used in all of this materials to describe a suppression of spectral weight with no obvious symmetry breaking.

What is the origin of the pseudogap?

• 3D perovskite structure.
• Parent compound insulating behavior is linked to lattice distortions in the form of breathing mode.
• SC emerges with doping. $T_c = 32 - 34$ K ($x \sim 0.38$) from insulating parent compound.
• No magnetic order. SC is phonon-mediated (isotope shift in $T_c$)

Electronic structure of the Parent Compound
Freezed lattice of bipolarons

- The Brillouin zone is folded due to breathing distortions of insulating.
- The BaBiO$_3$ insulator is negative charge transfer insulator, similar to the nickelates.

Foyevtsova, Sawatzky, et al., PRB 91, 121114(R) (2015)
Plumb et al., PRL 117, 037002 (2016)
Fermi surface \((x = 0.34)\)

At temperatures below \(T_p\), a spectral weight near \(E_F\) is reduced.

Naamneh et al., arxiv:1808.06135
Electronic structure of BKBO: pseudogap

2. Precipitation of frozen bipolarons (metal-insulator phase mixture)

- Quasiparticle peak is absent.
- The spectral weight is suppressed below $T_p$.
- The reduction is isotropic at $E_f$.
- The redistribution of the weight is anisotropic at deep binding energies.

See also
- Karlow et al., PRB 48, 6499 (1993)
- Chainani et al., PRB 64, 180509 (2001)
Phase separation - cuts

Superconducting BKBO

Insulator + Metal

\[ T = 17 \text{K} \]

\[ \alpha \]

\[ \frac{I_{LowT}(E_F, k_F)}{I_{HighT}(E_F, k_F)} \]

Metal

\[ T = 200 \text{K} \]

Subtracted

Insulator

Naamneh et al., arxiv:1808.06135
Phase separation-Fermi Surface

Superconducting BKBO

T=17K  T=200K

Subtracted

Binding Energy (eV)

-0.3  -0.22  -0.16  -0.09  -0.02  -0.3

EF

X

M

Subtracted

-0.1

-0.19

-0.26

-0.32

-0.4

T>T_\text{p}

T<T_\text{p}

Single scaling value.

Naamneh et al., arxiv:1808.06135
Raman scattering

- Breathing distortion peak at all temperatures, in contrast with neutrons
- Local distortions embedded/fluctuating in a different global symmetry
- Similar findings in nickelates:

Naamneh et al., arxiv:1808.06135

Little happening in structural probes. Why is there an electronic transition to phase separation?
ARPES view of electronic scattering

Subtracted spectra

At X point (near vHs)

Onset when scattering at $E_F$ corresponds to electron mean free path $= 2a$.

$\rightarrow$ Formation of insulator impeded by (lack of) electronic coherence.

Naamneh et al., arxiv:1808.06135
Doping dependence of $T_p$

Naïve picture: Higher doping $\rightarrow$ lower $T_p$ (further from insulator) ... WRONG!

Scattering picture: Higher doping $\rightarrow$ less scattering $\rightarrow$ higher $T_p$ ... OBSERVED!
Conclusions

• Depending on definition, we observe two types of PG:
  
  – Appear below $T_p$ and be regarded as true bandgap whose origin and underlying symmetry had been obscured by phase separation.
  
  – Broad energy suppression approaching $E_f$ persisting to room temperature and characterized by an absence of QP peak.

• Both pseudogaps stem from bi-polarons interactions.

• The phase separation is driven by scattering rather than change in the lattice.
In Su-Schrieffer-Heeger model, (bi)polaron “wants” to hop.
Strong coupling doesn’t necessarily imply high mass.

Sous et al., arxiv: 1805.06109

FIG. 2. (Color online) Dependence of the effective mass of the low-energy bipolaron on $\lambda$, for $U = 0$ and $\Omega = 3.0$. $m_0 = 2m_e$ is twice the free electron mass. The bipolaron’s effective mass is defined as $m^* = \left( \frac{\partial^2 E_{BR}(K)}{\partial K^2} \right)^{-1} \bigg|_{K = K_{GIS}}$. The solid (dashed) lines are VED (MA) results. Note that $m^* \sim 2m_e$ in the strongly coupled regime, $\lambda > 1$. 
Our approach: *In situ* spectroscopy on thin films
Electronic structure of BKBO: pseudogap


Naamneh et al., arxiv:1808.06135
Minimizing the energy of the system with correspond to the O displacement.
Intermediate doping behaves as a suppression of metallic and insulator.
Doped “normal state” transport

Single crystals

Our films

$\rho(T)$ vs. $T$ for $x = 0.34$, $0.39$, $0.48$, $0.62$

Naamneh et al., arxiv:1808.06135

FIG. 3. The valence band spectra of Ba$_{1-x}$K$_x$BiO$_3$ ($x = 0.2$ and $0.33$) showing changes across the semiconductor-metal transition and a pseudogap over $\sim 70$ meV (arrow) for $x = 0.33$ at 5.3 K. The superconducting transition is not clear here due to the larger step size used. The inset shows the full valence band spectra.
TEM: Phase separation in BaPBiO$_3$

Structural polymorphs is detected by TEM in superconducting sample of BaPb$_{1-x}$Bi$_x$O$_3$.

The system is ordered in nano-stripes having different structures, tetragonal and orthorhombic.

Maximum Tc occurs when the superconducting coherence length matches the width of the partially disordered stripes.

Debates surrounding insulating phase

Classical picture
Bi charge order

VS.

Alternative proposal
“Bond disproportionation”

- Rice, Varma, et al in 80s: gap opened by attractive effective on-site interaction (-U)
- Not clear a priori whether we can trust single-electron calculations

Picture: Franchini et al., PRB 81, 085213 (2010)

e.g.: Foyevtsova et al., PRB 91, 121114(R) (2015)
The evolution of constant energy map with doping up to superconductivity.

Percolation picture from insulator to superconducting
Polarization dependence

Plumb et al., PRL 117, 037002 (2016)
Angle-resolved photoemission spectroscopy

\[ k_\parallel = K_\parallel = \frac{1}{\hbar} \sqrt{2mE_{\text{kin}} \cdot \sin \theta} \]
\[ k_\perp = \frac{1}{\hbar} \sqrt{2m(E_{\text{kin}} \cos^2 \theta + V_0)} \]

ARPES can map electronic structure in 4 dimensions

\((E, k_x, k_y, k_z)\)


• Polaron cannot move independently when there lattice distortions overlap.
• LDA methods successfully compute most aspects of the band structure of BaBiO$_3$.
• The electron correlations are weak.