Ubiquitous generalized ARPES signatures of electron fractionalization in quasi-low dimensional metals

G.-H. Gweon, J.D. Denlinger¹, J.W. Allen
University of Michigan, Department of Physics
¹ permanent address now Advanced Light Source, LBNL
C.G. Olson
Ames Laboratory, University of Iowa
H. Höchst
Synchrotron Radiation Center, University of Wisconsin
J. Marcus and C. Schlenker,
LEPES, CNRS, Grenoble
L.F. Schneemeyer
Bell Laboratories, Lucent Technologies

Supported at U-M by U.S. DoE and NSF

Angle resolved photoemission spectroscopy (ARPES) to measure $\rho (k,\omega)$

- Photon In
- (Photo-)Electron Out
- Electron KE, $h\nu$, $\Rightarrow$ bind. en. $\omega$
- Angles $\theta, \phi \rightarrow$ k-par, cons. at surf.
- k-perp -- not conserved, must model surface potential
- Electron Energy Distribution ($\omega$) $= \rho (k,\omega)$ x Fermi function x (ARPES cross-section)

MDC (fix $\omega$, scan $k$) EDC (fix $k$, scan $\omega$) “FS” map ($\omega$=E_F, scan k region)

Photo-electron lifetime gives $\Delta k$-perp and extra $\Delta \omega$ for 3d crystals

low-dimension better!
Ubiquitous generalized ARPES signatures of electron fractionalization in quasi-low dimensional metals

**Luttinger liquid (Tomonaga-Luttinger model)**

spectral function much different from FL

Meden & Schönhammer ’92, Voiit ’93,

**TL lineshape**

- two features: holon and spinon
- power law tails
- spinon:
  - $\alpha > 1/2$ edge
  - $\alpha < 1/2$ peak (shown)
- gap to $E_F$ except for $k=K_F$

k-summed spectrum $\rho_{\text{LOC}}(\omega)$ approaches $E_F$ as power law in $\alpha$ -- even though system metallic!!

CDW fluctuations can give NFL pseudogap & mimic $\Sigma_A(k,E_F) = 0$

---

**Early Experimental Motivations**

Cuprate ARPES NFL lineshapes $\rightarrow$ Signal of LL?

Quasi-1-d PES, $\Sigma_A(k,0) = 0 \rightarrow$ LL? CDW pseudogap?

---

Dr. Jim Allen, Univ of Michigan (KITP Correlated Electrons Program 9/17/02)
Ubiquitous generalized ARPES signatures of electron fractionalization in quasi-low dimensional metals

**Low-D Metals and Fermi Surfaces**

- **Li$_{0.9}$Mo$_6$O$_{17}**
  - Non-FL, Non-CDW (24K), SC (1.9K)
- **K$_{0.3}$MoO$_3**
  - Non-FL Spin gapped CDW (180K)
- **AMo$_6$O$_{17}$ (A=Na,K)**
  - Hidden Nesting CDW (~100K)
- **HTSC cuprates**
  - Non-FL SC

**G.-H. Gweon thesis**

- 

**Dimensionality of E$_F$ Electronic Structure**

1. Low-D Metals and Fermi Surfaces
2. "Strangeness"

**TiTe$_2$ Fermi liquid lineshape fits near k$_F$**

- Claessens et al
  - PRL, 1992
- Not FL lineshape at bottom of band
- Quadratic tails for k near k$_F$
- Can remove electron for k > k$_F$ because of hole/particle pairs in many body ground state
- T = 20K
  - $\Delta k = 0.07 \AA^{-1}$
  - $\Delta \omega = 35$ meV

**University of Michigan**

**FESP02--Groningen**
Ubiquitous generalized ARPES signatures of electron fractionalization in quasi-low dimensional metals

Li$_{0.9}$Mo$_6$O$_{17}$ properties consistent with LL above a mystery phase at 24K

- Schlenker (‘85)
  - Specific heat

- Also 1.9 K SC
  - Mystery phase below 24 K
    - ρ upturn
    - weak C$_V$ anomaly
    - no gap > 1 meV
    - no CDW, SDW in x-ray diffraction (Pouget, 2001)

- diGiorgi (‘88)
  - Reflectivity
    - 300K, 4K same

- Schlenker (‘93)
  - Linear!
    - Resistivity

- Greenblatt (‘84)
  - Magnetic susceptibility

Temperature dependence in Li$_{0.9}$Mo$_6$O$_{17}$ PES
no Fermi edge, no E$_F$ gap opening

- Angle integrated mode
  - hν=33eV, ΔE=30meV

- Gradual change from 250K to 12K.
  - No Fermi edge. No gap. Only edge sharpening at small T

Dr. Jim Allen, Univ of Michigan (KITP Correlated Electrons Program 9/17/02)
Ubiquitous generalized ARPES signatures of electron fractionalization in quasi-low dimensional metals

Li$_{0.9}$Mo$_6$O$_{17}$ quasi 1-D Fermi surface

- Parallel to surface
  - Photon energy 24eV (A).
  - Scan two angles.

- Perpendicular to surface
  - Fix one angle (B).
  - Vary photon energy and other angle.

SRC, Ames/Montana beamline
$\Delta E = 150$meV
Denlinger, Gweon, Allen…, PRL ’99

Li$_{0.9}$Mo$_6$O$_{17}$ band structure (Whangbo ’88)

1D Fermi surface due to bands C and D

Bands A and B don’t cross $E_F$
Ubiquitous generalized ARPES signatures of electron fractionalization in quasi-low dimensional metals

**Li$_{1.9}$Mo$_2$O$_{17}$ – ARPES data $\Gamma$-$\gamma$ compared to TL theory for non-zero $T$ (Orgad)**

$\Delta E = 49$ meV, $\Delta \theta = 0.36^\circ$, $T = 250$ K

$\alpha = 0.9$, $v_{Fc} = 2v_{Fs}$, Finite $T$

**$v_c/v_s$ Dependence of Finite $T$ TL Line Shape**

$v_c$ is fixed to track the peak position

**Best choice**
Ubiquitous generalized ARPES signatures of electron fractionalization in quasi-low dimensional metals

\[
\alpha \text{ Dependence of Finite T TL Line Shape}
\]

![Graph showing the \(\alpha\) dependence of finite T TL line shape with different curves for Li Bronze ARPES Data, \(\alpha = 0.6\), \(\alpha = 0.7\), \(\alpha = 0.8\), \(\alpha = 0.9\), and \(\alpha = 1.0\).](image)

- \(\alpha = 0.6\): Too much weight
- \(\alpha = 0.7\): Too much weight
- \(\alpha = 0.8\): Still a little too much. But maybe OK?
- \(\alpha = 0.9\): OK, Best choice
- \(\alpha = 1.0\): OK

at limited to 1 in this theory

\((K, Na)\) purple bronzes (quasi 2d, CDW)
Fermi surface shows “hidden” one dimensionality

\[
\text{KMo}_6\text{O}_{17} \quad \hbar\nu = 22\text{eV}, \Delta E = 100\text{meV}, T = 150\text{K} (T_{\text{CDW}} = 80\text{K})
\]

3 weakly interacting quasi 1d chains
120 degrees apart
Ubiquitous generalized ARPES signatures of electron fractionalization in quasi-low dimensional metals

**NaMo$_6$O$_{17}$ ARPES Lineshapes Strange**

**Generalized ARPES signatures of electron fractionalization into density waves**

LL a paradigm theory for electron fractionalization. But seldom find materials which map neatly onto any non-FL model

Example: Can’t describe NFL lineshapes of spin-gapped blue bronze with ANY model

Need to break free from "toy model straightjacket!"
Look for generalized signatures of fractionalization

- Vanishing Weight at $E_F$ (No QP)
  e.g. Power Law (Anomalous Dimension $\alpha$) of LL
- Anderson-Ren Power Law Tail Line Shape (Anom. Dim.)
- Two (or More) Objects Moving At Different Speeds:
  e.g. Holon (Peak) and Spinon (Peak or Edge) of LL
- Sharp MDC, Broad EDC (Orgad et al ’01)
Ubiquitous generalized ARPES signatures of electron fractionalization in quasi-low dimensional metals

**Progressive angle integration for FL (TiTe$_2$) and LL (Li purple bronze)**

- **TiTe$_2$**
  - ARPES data angle sum to Fermi edge
  - Fermi edge
  - Angle int. $T=300$ K $h\nu=21.2$ eV $\Delta E = 33$ meV

- **Li$_{0.3}$Mo$_{0.7}$O$_{17}$**
  - ARPES data angle sum to power law
  - $\alpha = 0.9$

**Vanishing k-summed $E_F$ Weight?**

- **TL model**
  - $T=300$ K $\Delta E = 33$ meV
  - $\alpha=1.0$

- **Quasi 1d Li$_{0.3}$Mo$_{0.7}$O$_{17}$**
  - $T=300$ K $h\nu=21.2$ eV $\Delta E = 33$ meV
  - $\alpha=0.9$

- **Quasi 1d K$_{0.3}$Mo$_{0.7}$O$_{17}$**
  - $T=300$ K $h\nu=21.2$ eV $\Delta E = 33$ meV
  - $\alpha=0.7$

- **Quasi 2d NaMo$_{0.5}$O$_{13}$**
  - $T=300$ K $h\nu=21.2$ eV $\Delta E = 33$ meV
  - $\alpha=0.3$

- **Bi2212**
  - $T=115$ K $h\nu=22eV$ $\Delta E = 16$ meV
  - $\alpha=0$

- **TiTe$_2$**
  - $T=25$ K $h\nu=21.2$ eV $\Delta E = 35$ meV
  - $\alpha=0$

- **(0,0) $\rightarrow$ ($\pi$,0)** may be $\alpha\neq 0$


**University of Michigan**  **FE P02--Groningen**

---

Dr. Jim Allen, Univ of Michigan (KITP Correlated Electrons Program 9/17/02)
Ubiquitous generalized ARPES signatures of electron fractionalization in quasi-low dimensional metals

**Anderson-Ren lineshape visualization**

- **Break follows dispersion** $\epsilon(k)$
- **Common power law for all spectra** $|E-E_F|^{-\alpha}$
- **Cutoff**
- **Bi2212**
  - Kaminsky '01
  - $\Gamma (0,0) - \Gamma (\pi,\pi)$
  - $h\nu = 22$ eV
  - $T = 115$ K

**Visualization of Bi2212 ARPES lineshape**

- Anderson/Ren, 1990

**But Not LL!**

- LL sing. moves with $\epsilon_k$

**NO for FL TiTe$_2$**

**AR lineshape for quasi 1-d systems**

- YES for Li$_{0.9}$Mo$_{0.17}$O$_{17}$
  - $|\alpha| = 0.29$
  - $\alpha = 0.71$
  - not 0.9 but > 0.5

- YES for K$_{0.3}$MoO$_3$
  - $|\alpha| = 0.8$
  - $\alpha = 0.2$
  - $\neq 0.7$, blue bronze trouble
  - spin gap breaks
  - AR connection to $\alpha$
Ubiquitous generalized ARPES signatures of electron fractionalization in quasi-low dimensional metals

Narrow MDC and Wide EDC

Orgad et al, PRL 86, 4362 (2001)

Reported for Bi2212 and static stripe cuprate

T=0, LL
Kinematic Constraint of Decomposition of e− into Spinons and Holons

Holds for finite T and LE as well. Generalized to other Density Waves?

Sharp MDC and Broad EDC? For quasi-1d systems

Both MDC Width and EDC Width Intrinsic
Ubiquitous generalized ARPES signatures of electron fractionalization in quasi-low dimensional metals

**All Four Fractionalization Signatures in Quasi-2d (hidden 1-d) NaMo₆O₁₇**

1. Power law at $E_F$
2. A-R lineshape
3. Badly scattered holon from Na disorder
4. Broad EDC, sharp MDC

FS defined by unscattered spinon (peak since $\alpha < 0.5$)

NaMo₆O₁₇

$T = 300 \text{K}$
$h\nu = 21.2 \text{eV}$
$\Delta E = 33 \text{meV}$

$\alpha = 0.3$

**Bi2212 Line Shape**

Na purple bronze spectra as Rosetta stone for recognizing fractionalization in the presence of disorder in HTSC cuprates

$\theta/\phi$

Bi2212 Dessau '93 PRL

$\% \text{of } M'K^*$

$E - \mu = 0 ( \text{eV} )$

$k = k_F$
Ubiquitous generalized ARPES signatures of electron fractionalization in quasi-low dimensional metals

**Early statements that the cuprate “background” is intrinsic**

Can fit Olson et al Bi2212 data with MFL (FL) only if remove “background” 15 (60) times larger than implied by entire VB.

Liu, Anderson, Allen

Vibronic analogy
Also, further arguments in LANL workshop proceedings, (Addison-Wesley, 1990).

**T- linear resistivities in purple bronzes!**

Quasi-1d K blue
Brutting, ’95

Quasi-1d Li purple
Schlenker et al (’93)

Quasi 2-d
Hidden-1d
Na,K purple

R. Buder et al
Ubiquitous generalized ARPES signatures of electron fractionalization in quasi-low dimensional metals

<table>
<thead>
<tr>
<th>Scorecard of generalized fractionalization signatures</th>
</tr>
</thead>
<tbody>
<tr>
<td>TiTe₂</td>
</tr>
<tr>
<td>no signatures</td>
</tr>
<tr>
<td>quasi 1-d Li purple bronze (1, 2, 3, 4)</td>
</tr>
<tr>
<td>quasi 1-d K blue bronze (1, 2, --, 4)</td>
</tr>
<tr>
<td>quasi 2-d (hidden 1-d) Na purple bronze (1, 2, 3, 4)</td>
</tr>
<tr>
<td>quasi 2-d Bi2212 SC cuprate (--, 2, 3, 4)</td>
</tr>
</tbody>
</table>

**FL example**

**LL example**

**spin-gapped no lineshape works**

**melted holon \( \alpha < \frac{1}{2} \)**

**spinon peaky**

Note: no microscopic derivation of AR lineshape

HINTS OF A BIGGER PICTURE!