Abstract: In underdoped cuprate superconductors, a rich competition occurs between superconductivity and charge density wave order (CDW). Under debate, however, is whether rotational symmetry breaking (nematicity) also plays a central role -- whether it occurs intrinsically and generically or merely as a consequence of other orders. Here we employ resonant x-ray scattering in stripe-ordered (La,X)2CuO4 to probe the relationship between electronic nematicity of the Cu 3d orbitals, structural orthorhombicity of the (La,X)2O4 layers and CDW order. We find distinct temperature dependences of the structural orthorhombicity and the electronic nematicity, with the electronic nematicity, but no structural orthorhombicity enhancement below the onset of CDW order. These results indicate electronic nematicity is an order parameter that is distinct from a purely structural order parameter in underdoped cuprates.
Outline

• Charge density wave (CDW) order in the cuprates

• Comparison between CDW order in YBCO and La-based cuprates

• Symmetry of CDW order in the cuprates

• Nematicity in stripe ordered cuprates
Outline

- Charge density wave (CDW) order in the cuprates
- Comparison between CDW order in YBCO and La-based cuprates
- Symmetry of CDW order in the cuprates
- Nematicity in stripe ordered cuprates
Cuprate high-temperature superconductors

La$_{2-x}$Sr$_x$CuO$_4$

Low energy physics is dominated by the CuO$_2$ planes

O 2p, Cu 3d$_{xz, yz}$
Cuprate high-temperature superconductors

La$_{2-x}$Sr$_x$CuO$_4$

Low energy physics is dominated by the CuO$_2$ planes
Density wave order in the cuprates

La$_{1.475}$Nd$_{0.5}$Sr$_{0.125}$CuO$_4$

Elastic Neutron scattering

Unidirectional Spin and charge order (stripes) first observed in the cuprates by neutron scattering (Tranquada et al., Nature 1995)

Charge density wave (CDW) peak

Spin density wave (SDW) peak

Half-filled charge stripe

Undoped AF regions
Density wave order in the cuprates

Some characteristic features of “stripes” in La-based cuprates

- Unidirectional spin order (SO) and charge order (CO)
- CDW with period ~4 lattice constants (4\(a_1\))
- Associated with a suppression of superconductivity at \(x = 1/8\)
- Stabilized by LTT structural distortion

M. Hücker
PHYSICAL REVIEW B 83, 104506 (2011)
Density wave order in the cuprates

Some characteristic features of “stripes” in La-based cuprates

- Unidirectional spin order (SO) and charge order (CO)
- CDW with period ~4 lattice constants (4\alpha)
- Associated with a suppression of superconductivity at x = 1/8
- Stabilized by LTT structural distortion

M. H"ucker
PHYSICAL REVIEW B 83, 104506 (2011)
Charge order is generic to the cuprates

Scanning tunneling microscopy

\[ \text{Ca}_{1.88}\text{Na}_{0.12}\text{CuO}_2\text{Cl}_2 \]

Observations of density wave order by STM

- Davis group
- Kapitulnik group
- Yazdani group
- Hoffmann group
- Hudson group
- ...

Differential tunneling conductance

Hanaguri Nature 2004

Khosaka Science 2008
Charge density wave order in YBCO??

$\text{YBa}_2\text{Cu}_3\text{O}_{6+x}$

- Bilayer cuprate
- Orthorhombic structure ($a \neq b \neq c$)
- Doped by O atoms intercalated into “chain” layer far from the CuO$_2$ planes
- Low levels of disorder
- High $T_{c,mag} = 94.2$ K
- Oxygen orders in the chain layer

Ex: Ortho III ordered YBa$_2$Cu$_3$O$_{6.75}$

(a) full chains empty chain

chain layer
CuO$_2$ planes
Y

(c) Cu1 f Cu16

[Diagram showing the structure of YBCO with annotations for full and empty chains, chain layers, CuO$_2$ planes, and lattice parameters]
Charge density wave order in YBCO??

\[ \text{YBa}_2\text{Cu}_3\text{O}_{6+x} \]

- Bilayer cuprate
- Orthorhombic structure \((a \neq b \neq c)\)
- Doped by O atoms intercalated into “chain” layer far from the \(\text{CuO}_2\) planes
- Low levels of disorder
- High \(T_{c,max} = 94.2\) K
- Oxygen orders in the chain layer

Ex: Ortho III ordered \(\text{YBa}_2\text{Cu}_3\text{O}_{6.75}\)

(a) Full chains empty chain

Chain layer

\(\text{CuO}_2\) planes

\(c\)

\(a\)

Culf Cule
Indirect evidence of density wave order in YBa$_2$Cu$_3$O$_{6+y}$

- Electron pocket from quantum oscillations in low doped YBCO
- Fermi surface (ARPES)
- Hole like Fermi surface measured in cuprates by angle resolved photoemission
- Underdoped $(0,0)$
- Overdoped $(\pi,\pi)$
Indirect evidence of density wave order in YBa$_2$Cu$_3$O$_{6+x}$

Electron pocket from quantum oscillations in low doped YBCO

Fermi surface (ARPES)

Hole like Fermi surface measured in cuprates by angle resolved photoemission

Evidence of density wave order in YBa$_2$Cu$_3$O$_{6+\delta}$

High field NMR in YBCO interpreted as evidence for charge order

Splitting of in plane Cu$^{53}$ peaks associated with charge density variation

- weak charge order ($\delta p = 0.03$)
- Only observed in high magnetic field (28.5T)

Tao Wu et al., Nature 2011
CDW order in YBCO

Long-Range Incommensurate Charge Fluctuations in \((\text{Y, Nd})\text{Ba}_2\text{Cu}_3\text{O}_{6+x}\)

Using resonant x-ray scattering, Ghiringhelli et al. detected CDW order in underdoped YBCO

- CDW peaks at \([0.3 \ 0 \ L]\) and \([0 \ 0.3 \ L]\) in detwinned, orthorhombic samples
- Incommensurability of 0.3 (instead of 0.25 as in La-based cuprates)

CDW order in YBCO

Long-Range Incommensurate Charge Fluctuations in (Y,Nd)Ba$_2$Cu$_3$O$_{6+x}$

Using resonant x-ray scattering, Ghiringhelli et al. detected CDW order in underdoped YBCO

- CDW peaks at [0.3 0 L] and [0 L 0.3 L] in detwinned, orthorhombic samples
- Incommensurability of 0.3 (instead of 0.25 as in La-based cuprates)

CDW order in YBCO

Long-Range Incommensurate Charge Fluctuations in (Y,Nd)Ba$_2$Cu$_3$O$_{6+x}$

G. Ghiringhelli,*, H. In Tomita,† M. Minoda,‡ S. Bianco-Cessa,‡ C. Maazou,†
N. E. Brookes,§ G. M. De Luca,† A. Franz,†† D. O. Hawthorn,∥ H. He,∥ T. Loew,∥
M. Moretti Sala,∥ D. C. Petti,∥ M. Salluzzo,∥ E. Schinde∥ G. A. Sawatzky,*
F. Wachtler,∥ B. Keimer,*∥ I. Blaudeau*

Using resonant x-ray scattering, Ghiringhelli et al. detected CDW order in underdoped YBCO

- CDW peaks at [0.3 0 L] and [0 0.3 L] in detwinned, orthorhombic samples
- Incommensurability of 0.3 (instead of 0.25 as in La-based cuprates)

CDW order onsets at \( \sim 150 \text{ K} \) and peaks in intensity at \( T_c \), the superconducting transition temperature.

CDW order in YBCO

CDW order onsets at ~150 K and peaks in intensity at $T_c$, the superconducting transition temperature.

Indirect evidence of density wave order in YBa$_2$Cu$_3$O$_{6+x}$

Electron pocket from quantum oscillations in low doped YBCO

Fermi surface (ARPES)

Hole like Fermi surface measured in cuprates by angle resolved photoemission

Shen et al.

Plate et al.

CDW order in YBCO in magnetic field

Hard x-ray scattering

Ortho VIII ordered YBCO

Competition between SC and CDW orders:
A magnetic field perpendicular to the planes suppresses superconductivity and enhances charge density wave order.
Density wave order in the planes of Ortho III YBCO

\[ \text{YBa}_2\text{Cu}_3\text{O}_{6.75} (\rho = 0.133, T_c = 75.2 \text{ K}) \]

- CDW order in the CuO\(_2\) planes
- CDW order present in high purity, oxygen-ordered samples
- Insight into microscopic character of CDW order

(a) full chains empty chain

chain layer
\[ \text{CuO}_2 \]
planes

\[ \text{a} \quad \text{c} \]

\[ \text{Y} \quad \text{Ba} \quad \text{O} \]

\[ \text{Cu}_1 \quad \text{Cu}_2 \]

(f) \[ I_{\text{amp}} / I_0 \text{ (arb.)} \]

\[ 0 \quad 50 \quad 100 \quad 150 \quad 200 \]

\[ T(\text{K}) \]

\[ \pm 933.6 \text{ eV (o-III)} \]
\[ [0.33 \ 0.15] \]

\[ \pm 931.3 \text{ eV} \]
\[ [0.30 \ 0.135] \]

Achkar et al. PRL 109, 167001 (2012)
CDW order in the other cuprates

\( \text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8+\delta \) (Bi2212)

\( \text{Bi}_2\text{Sr}_2\text{La}_x\text{CuO}_6+\delta \) (Bi2201)


Comin et al. Science (2014)
Charge ordering in the electron-doped superconductor Nd$_{2-x}$Ce$_x$CuO$_4$

Eduardo H. da Silva Neto,$^{2,8,9,10}$ Ricardo Comin,$^{1,7,9}$ Frederico Her,${}^{10}$ Romany Sarma,$^{10}$
Yeqing Jiang,$^{10}$ Richard L. Greene,$^{5}$ George A. Sawatzky,$^{11,12}$ Andrea Hamerschift$^{11,12}$

[Graph showing charge ordering data]

CDW order in electron doped

Charge ordering in the electron-doped superconductor Nd$_{2-x}$Ce$_x$CuO$_4$

Characteristics of CDW order in the cuprates

What is common or different about the CDW order observed in different cuprate families?
CDW onset temperature peaked near $p = 1/8$

YBa$_2$Cu$_3$O$_{6+x}$

La$_{1.8-x}$Eu$_{0.2}$Sr$_x$CuO$_4$

Achkar et al. unpublished
Banco-Canosa PRB 14
Hucker PRB 14
CDW onset temperature peaked near $p = 1/8$

YBa$_2$Cu$_3$O$_{6+x}$

La$_{1.8-x}$Eu$_{0.2}$Sr$_x$CuO$_4$

Achkar et al. unpublished
Banco-Canosa PRB 14
Hucker PRB 14

Fink PRB 2011
CDW intensity peaked near $p = 1/8$

YBCO

CDW intensity peaked near $p = 1/8$, coincident with a suppression of $T_c$. Peak at $[0 K L]$

- Ordered
- Disordered
- $T_c$
- $T_c$ line

Achkar et al. unpublished
Competition between CDW order and superconductivity: Magnetic field dependence

Similar enhancement of CDW order in YBCO and LBCO observed by suppressing SC with an applied magnetic field

Chang Nat. Phys. 2012

Hucker PRB 2013
Short range order

Correlation length of CDW order is short and similar in magnitude (~20 – 200 Å) in different cuprates

La$_{1.45}$Nd$_{0.4}$Sr$_{0.125}$CuO$_4$

Achkar et al. PRL 110, 017001 (2013)
Correlation length = 73 Å

YBCO

Achkar et al. PRL 113, 107002 (2014)
Correlation length = 50 Å

Also, similar peak intensities (Thampy PRB 2013)
Short range order: Effect of disorder in YBCO

YBa$_2$Cu$_3$O$_{6.67}$

Achkar et al. PRL 113, 107002 (2014)

Changing the degree of disorder (disordering the oxygen ortho order in the chain layer) in YBCO:

- Reduction in peak intensity
- No effect on the incommensurability
- No effect on correlation length
Short range order: Effect of disorder in YBCO

\[ Y{\text{Ba}}_2{\text{Cu}}_3{\text{O}}_{6.67} \]

Achkar et al. PRL 113, 107002 (2014)

Temperature dependence

Changing the degree of disorder (disordering the oxygen ortho order in the chain layer) in YBCO:

- Reduction in peak intensity
- No effect on the incommensurability
- No effect on correlation length
- No effect on temperature dependence
Short range order: CDW/SC competition

Monte Carlo calculations of non-linear sigma model
(multi-component order parameter)

CDW order may be intrinsically short-ranged due to competition with superconductivity and/or frustration between unidirectional domains of CDW order

Unidirectional order: stripes

La-based cuprates

- Tilting of CuO$_2$ octahedra along Cu-O bond in the LT phase breaks $C_2$ symmetry and is understood to produce stripe-like CDW/SDW order
- Tilt direction alternates between planes

Tranquada 1995
Tranquada 1996
Unidirectional order: stripes

La-based cuprates

- Tilting of CuO$_2$ octahedra along Cu-O bond in the LTT phase breaks C$_2$ symmetry and is understood to produce stripe-like CDW/SDW order
- Tilt direction alternates between planes

Tranquada 1995
Tranquada 1996
Unidirectional CDW: YBCO

Blackburn PRL 2013
Blanco-Canosa PRL 2013
Blanco-Canosa PRB 2014
Achkar unpublished
Also: Comin Science 2015
Achkar arXiv 2014

YBCO is orthorhombic
Chain layer
CuO$_2$ planes

Bi-directional CDW
Unidirectional CDW
(K peak but no H peak)

Blanco-Canosa PRB 2014
Unidirectional CDW: YBCO

Blackburn PRL 2013
Blanco-Canosa PRL 2013
Blanco-Canosa PRB 2014
Achkar unpublished
Also: Comin Science 2015
Achkar arXiv 2014

Bi-directional CDW

YBCO is orthorhombic

Chain layer
CuO₂ planes

Unidirectional CDW (K peak but no H peak)

Blanco-Canosa PRB 2014
Unidirectional CDW: YBCO

Blackburn PRL 2013
Blanco-Canosa PRL 2013
Blanco-Canosa PRB 2014
Achkar unpublished

Also: Comin Science 2015
Achkar arXiv 2014

YBCO is orthorhombic

Bi-directional CDW

Unidirectional CDW
(K peak but no H peak)

Blanco-Canosa PRB 2014
Unidirectional CDW: YBCO

Blacksbur PRL 2013
Blanco-Canosa PRL 2013
Blanco-Canosa PRB 2014
Achkar unpublished

Also: Comin Science 2015
Achkar arXiv 2014
CDW doping dependence

$YBa_2Cu_3O_{6.335}$  \hspace{1cm} $\rho \sim 0.06, \ T_c \sim 12 \ K$

No oxygen order in the chain layer

No measurable peak intensity along $H$

Also, co-existence of CDW order with quasi-static AF order at this doping (although not SDW order that has a 2Q relation to CDW order, like the stripes in La-based cuprates).

Achkar et al. unpublished
Incommensurability
(Period of CDW order): YBCO

YBCO CDW ($H \approx L$)
- This work (SXR)
- Blanco-Carassa 14 (SXR)
- Blackburn 13 (HXR)

YBCO CDW ($0 \approx K \approx L$)
- This work (SXR)
- Blanco-Carassa 14 (SXR)
- Hacker 14 (HXR)
- Blackburn 13 (HXR)

Achkar et al. unpublished
Incommensurability
(Period of CDW order): YBCO
Bi2212: Incommensurability

STM Bi2212

Kohsaka Nature 2008
Fujita JPSJ 2011

\[ q^* \]

\[ p \]

0.20 0.25 0.30
0.08 0.12 0.16
Bi2212: Incommensurability

STM Bi2212

Kohsaka Nature 2008
Fujita JPSJ 2011

Q_{CDW} connects ends of Fermi-surface arcs (Hot-spots)

Ghiringhelli 2012
Sachdev PRL 2013
Efetov Nature Physics 2013
Dalla Torre arXiv 2014
Kohsaka Nature 2008
Fujita JPSJ 2011
Comin 2014
Bi2201: Incommensurability

$Q_{CDW}$ connects ends of Fermi-surface arcs (Hot-spots)

ARPES - UD15K

$k_x$ (units of $1/a_y$)

Max

Min

REXS - $Q_{GG}$

STM - $Q_{GG}$

Bi2201 - This work

Pb-B2201 - Ref. 7

RSXS, STM, ARPES: Comin et al. Science (2014)
Incommensurability: LBCO

Doping dependence of incommensurability is different in La-based cuprates (Yamada plot)

YBCO CDW ($H \neq L$)
- This work (SXR)
- Blanco-Canoa 14 (SXR)
- Blackburn 13 (HXR)

YBCO CDW ($0 \neq L$)
- This work (SXR)
- Blanco-Canoa 14 (SXR)
- Hucker 14 (HXR)
- Blackburn 13 (HXR)

LBCO (CDW)
- Hucker 14 (NS)

Yamada 1998
Hucker 2011

Achkar et. al unpublished

CDW wavevector

$\delta$ (r.l.u.)

$p$ (holes/Cu)
Static spin density wave (SDW) order

La-based cuprates
Static SDW order with twice the period of the charge order

BSCCO, YBCO
Spin gap – No static SDW order related to CDW order

Tranquada 1995
Orbital Symmetry of CDW order


Orbital Symmetry of CDW order

CuO$_2$ plane

\[ \lambda = \frac{2\pi}{Q} \]

$O_\perp$ $O_\parallel$ Cu
Symmetry of CDW order

$O_{\perp}$  \hspace{1cm} $O_{\parallel}$  \hspace{1cm} Cu

Cu sublattice  \hspace{2cm} s symmetry CDW

$O$ sublattice  \hspace{2cm} $s'$ symmetry CDW

$\lambda = 2\pi/Q$
Symmetry of CDW order

O↓
Cu sublattice
s symmetry CDW

O↑
s′ symmetry CDW

Cu

λ=2π/Q

Sachdev and La Placa, PRL 2013
Efetov, Meier and Pepin, Nat. Phys. 2013
Metlitski and Sachdev, PRB 2010
Vojta and Rosch PRL 2008
Atkinson, Kampf and Bulut NJP 2015
Wang and Chubukov PRB 2014
Kee, Chen and Hu PRB 2007
Li, Wu and Lee PRB 2006
Chowdhury and Sachdev arXiv 2014
Thomson and Sachdev arXiv 2014
...
$d$ symmetry charge order from STM

Real space

Fourier Transforms (Q space)

O$_{x}$+O$_{y}$ sublattices

BSCCO

STM

$Q$

Cu O Cu

Cu O Cu

$Q$

F

$\delta$ symmetry

Fujita et al. PNAS 2014
$d$ symmetry charge order from resonant x-ray scattering

Report of $d$-symmetry CDW in YBCO from azimuthal angle dependent resonant x-ray scattering

Cu L edge resonant x-ray scattering

Symmetry of density wave order in La-based cuprates

Is CDW different in La-based cuprates?

- Unidirectional spin (SO) and charge (CO)
- More dramatic suppression of superconductivity at $x = 1/8$
- Different doping dependence to CDW incommensurability
- Orbital symmetry of CDW order

Resonant X-ray Scattering

Tune photon energy to an x-ray resonance

On resonance, the atomic scattering form factor, $f_j$, is sensitive to orbital symmetry

$$I_{sc}(\vec{Q}) \propto \left| \sum_j f_j e^{-i2\pi \vec{Q} \cdot \vec{r}_j} \right|^2$$

$$I_{sc}(\vec{Q}, \omega, \vec{r}) \propto \left| \sum_j (\vec{r} \cdot \vec{F}_j(\omega) \vec{r}) e^{-i2\pi \vec{Q} \cdot \vec{r}_j} \right|^2$$

Scattered photon polarization  Incident photon polarization

$$F = \begin{bmatrix} f_{xx} & f_{xy} & f_{xz} \\ f_{yx} & f_{yy} & f_{yz} \\ f_{zx} & f_{zy} & f_{zz} \end{bmatrix}$$
CDW symmetry

Holes in O \(2p_x\) or \(2p_y\) states form two distinct sublattices relative to the CDW direction \(Q\).

\[
\begin{align*}
O_{\perp} & & O_{\parallel} & & Cu \\
\end{align*}
\]

\[
\lambda = 2\pi/Q
\]

Components of a tensoral equivalent of the structure factor
Experimental scheme

Rotate the sample geometry and photon polarization relative to the $a$, $b$ and $c$ axes

Side view

Top view ($\phi = 0$)

REIKS beamline at the Canadian Light Source. Hawthorn et al.

Comin 2014
Achkar 2014
Why would CDW symmetry be different?

LBCO (La-based cuprates)

$s'$ symmetry CDW+SDW

$2\pi/Q$

BSCCO, NCCOC, (YBCO?)

$d$ symmetry CDW

$\lambda=2\pi/Q$

$d$-symmetry CDW order is unfavorable for static spin density wave order
SDW order and CDW symmetry

Theoretical support for a relation between static SDW order and CDW symmetry

Thomson and Sachdev arXiv:1410.348

• “... the presence of antiferromagnetic order decreases the magnitude of the d-form factor; this trend is consistent with recent observation of a dominant s′ form factor in the hole-doped cuprate with magnetic order, La$_{1.875}$Ba$_{0.125}$CuO$_4$.”

Fischer, Wu, Paramekanti, Lawler, Kim New Journal Physics 2014

• A model with spin and charge stripes exhibits d/s′ ~0.1
CDW symmetry and Superconductivity

LBCO (La-based cuprates)

$s'$ symmetry CDW+SDW

$2\pi/Q$

BSCCO, NCCOC, (YBCO?)

$d$ symmetry CDW

$\lambda=2\pi/Q$

CDW symmetry may play a role in the competition with superconductivity
Scattering form factor: orbital symmetry dependence

O K edge (1s → 2p transition): sensitive to orbital symmetry of O 2p holes

\[ F = \begin{bmatrix} f_{xx} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \]  

\[ F = \begin{bmatrix} 0 & 0 & 0 \\ 0 & f_{yy} & 0 \\ 0 & 0 & 0 \end{bmatrix} \]
Symmetry of CDW order

\( O_\perp \quad O_\parallel \quad Cu \)

Cu sublattice \( s \) symmetry CDW

O sublattice \( s' \) symmetry CDW

\( \lambda = \frac{2\pi}{Q} \)

Sachdev and S. Pla, PRL 2013
Efetov, Meier and Pepin, Nat. Phys. 2013
Metlitski and Sachdev, PRB 2010
Vojta and Rosch PRL 2008
Atkinson, Kampf and Bulut, NJP 2015
Wang and Chubukov PRB 2014
Koo, Chen and Hu PRB 2007
Li, Wu and Lee PRB 2006
Chowdhury and Sachdev arXiv 2014
Thomson and Sachdev arXiv 2014
...