Q=0 Magnetic order in the pseudogap state of cuprates superconductors

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Using polarized neutron diffraction: 4F1 (LLB-Saclay) & D7 (ILL-Grenoble)

Magnetic order in the pseudogap state of high-Tc cuprates in 4 different families: YBCO, Hg1201, LSCO, Bi2212

There is a broken symmetry below T* which does not break the translation symmetry (Q=0) but breaks Time reversal symmetry

Intra unit cell antiferromagnetism (2 antiparallel moments)
Local Cu spins not enough ➔ another source of magnetism
Outline:

1) Introduction
2) Short range correlations near optimal doping
3) Tilt of the moment: In-plane and out-of-plane Magnetic components
4) Phase diagrams: Q=0 magnetic order in the pseudogap state, CDW and nematic order
Pseudo-Gap

- Mysterious phase which appears below $T^*$
- Anomalous magnetic and charge properties
  Common line at $T^*$  
  (Tallon & Loram)

Phase transition?
Which broken symmetry?

Heavy fluctuations around QCP
Superconducting mechanism?
**Motivation:** CC-loop order, Intra-unit-cell magnetic order

C.M. Varma, PRB 1997; PRB 2006

Breaks Time-reversal symmetry

**What are we looking for?**

Spin polarized neutron diffraction technique

**Staggered orbital moments**

$Q=0$ AFM order

4 States/Domains
Need for a polarized monochromatic neutron beam

- Nuclear Scattering
  Non spin flip: $- |F_N| -$

* Magnetic Scattering
  $$F_M = < \pm |\vec{\sigma} \cdot \vec{M}_\perp| - >$$
  $$\vec{M}_\perp = \vec{Q} \wedge \vec{M}_Q \wedge \vec{Q}$$
  $$\vec{M}_Q = \sum \vec{M} \exp^{-i\vec{Q}r}$$

Polarizing mirror

Flipper

Sample

Helmotz coil

H=10 G, P//H

$4F1/LLB$

$\lambda = 2.45 \text{ Å}$

Magnetic components $\perp \vec{Q}$

Spin-flip components $\perp \vec{P}$

P//Q to maximize magnetism in the Spin-flip channel

Flipping ratio:

$$R = NSF/SF = I^-/I^+ \quad (R \sim 50)$$

Neutron polarization:

$$p = (I^- - I^+)/(I^- + I^+) \sim 96\%$$

NSF: $$\frac{d\sigma}{d\Omega} = |F_N|^2$$

SF: $$\frac{d\sigma}{d\Omega} = |F_M|^2 + |F_N|^2 / R$$
Underdoped YBCO$_{6.6}$: Long range Intra unit Cell magnetic order

NSF: $\frac{d\sigma}{d\Omega} = |F_N|^2$

SF: $\frac{d\sigma}{d\Omega} = |F_M|^2 + |F_N|^2 / R$

$L$-scan
$(\xi_C > 75 \text{ Å})$

see also B. Fauqué et al, PRL (2006).
Order in the PG state (match $T^*$ resistivity)

Other reports of a phase transition at $T^*$ in YBCO:

- Resonant ultrasound spectroscopy

- Uniform magnetic susceptibility
  B. Leridon et al, EPL, 87 17011, (2009)

- Optical birefringence

- Polar Kerr effect ($\mu$rad) at $T_K$

Intra-unit cell nematicity by STM in Bi2212
M.J. Lawler et al, Nature 2010
different electronic density on both oxygens: Ox and Oy

$\Rightarrow$ No evidence in magnetic local probes ($\mu$SR, NQR, NMR)

LSCO: Mac Dougall, PRL (2008)
YBCO: Sonier, PRL (2008), Wu (2014)
Y124: Strassle PRL (2011)
Hg1021: Mounce, PRL (2013)
**Broken time-reversal symmetry**

**ARPES**

**Dichroism in ARPES at the M point**

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**Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$**

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**Kaminski, Nature 2002**

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**Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$**

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**Y. Sidis & P. Bourges  arXiv 1306.5124**
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YBCO\(_{6.85}\): nearly optimally doped

\(\text{YBa}_2\text{Cu}_3\text{O}_{6.85}: \text{Tc}=89 \text{ K}, p=0.15\)

\(1/\text{Flipping Ratio}=\text{FR}^{-1}=\text{SF/NSF} = \text{FR}_0^{-1} + \text{M}^2/\text{NSF}\)

- \(\text{FR}_0^{-1}\) calibrated on 004 and 200
- \(T_{\text{mag}} \sim 200 \text{ K}\)

L. Mangin-Thro et al, ArXiv 1501.04919

Magnetic intensity on \(Q=(100)\) and \(Q=(101)\) (4 times weaker than YBCO\(_{6.6}\))
Multi-detectors diffratometer: D7 (ILL)

- Polarized neutron with 120 detectors ➔ H-scan
- XYZ polarization analysis ➔ magnetic intensity
- Range of correlations ($\lambda \sim 5$ Å, cold neutrons, good q-resolution)
\textbf{YBCO}_{6.85} : Short range magnetic order

Finite inplane Correlations

$T = 100K$

$\xi_{ab} \sim 20a \sim 75 \, \text{Å}$

$\xi_{ab} > \xi_{\text{CDW}} \sim 8a$

$\xi_{ab} : \text{no clear } T\text{-dependance}$

\textit{L. Mangin-Thro et al, ArXiv 1501.04919}
H-integrated intensity

\[ \bar{I} = \frac{N}{\sum_{i=1}^{N} I_i / N} = \frac{BG}{\bar{I}} + I_0 \frac{\Delta q}{q_N - q_1} \sqrt{\frac{\pi}{4 \ln 2}} \]

(Over ~ 10 detectors)

hardly correlated along c

\[ T=100K: \Delta q = 0.65 \text{ rlu}, \xi_c \sim 0.5 \text{ c} \]

L. Mangin-Thro et al, ArXiv 1501.04919
Doping dependence of the peak intensity

Magnetic intensity vs T_{mag}

Moment \sim 0.1 \mu_B

Long range correlations (underdoped)

Short range Correlations (near optimal doping)

\[ p \sim 0.09 \]

\[ p \sim 0.13 \]

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For $Q=(1,0,1)$:

Polarization analysis:

\[ I_{P//Q} = I_{P//z} + I_{P\perp Q} \]

Angle $(M,c^*) \sim 45 \text{ deg}$

Weak or zero structure factor for $Q=(2,0,1)$
One CuO$_2$ layer

HgBa$_2$CuO$_{4+d}$: $T_c=75$ K

Polarization analysis: $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$

- Angle $(M,c^*) \sim 20 \pm 20 \text{ deg}$

YBCO$_{6.85}$: Polarization analysis D7/H-integrated intensity

Magnetic Components

\[ I_{Z}^{SF} \propto (1 - q_i^2) M_c^2 + \frac{q_i^2}{2} M_{ab}^2 \sim M_c^2 \]

\[ I_{Y}^{SF} \propto \frac{1}{2} M_{ab}^2 + I_Z \sin^2 \beta \]

\[ I_{X}^{SF} \propto \frac{1}{2} M_{ab}^2 + I_Z \cos^2 \beta \]

- **Ising Character** above $T_{mag}$ (as expected for Loop Currents)

- **Tilt appears** below $T_{mag}$ (40 deg at 100K)

L. Mangin-Thro et al, ArXiv 1501.04919
Diffuse scattering

\[ Q \sim (0.9, 0, 0) \]

« Critical behaviour »

\[
I_Z^{SF} = M_C^2 + BG \\
\left( I_X^{SF} + I_Y^{SF} \right)/2 = (M_C^2 + M_{ab}^2)/2 + BG \\
\alpha (M_{ab}^2 - M_C^2)
\]
Tilt why?

- Loop order

Spin-orbit coupling in CC phase


Quantum superposition of the 4 states

Y. He & C.M. Varma, PRB 86, 035124 (2012).

- Loop order on the CuO$_6$ octaedra

C. Weber et al, PRL 102, 017005 (2009)
S. Lederer & S. Kivelson PRB85, 155130 (2012)

not ok: tilt=0 for L=0

- Neutron cross-section:

Parity odd operators (broken inversion)

Magnetic quadrupole

S.V. Lovesey et al, ArXiv 1408.5562
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YBCO phase diagram: comparison with CDW

V. Baledent et al.,
*PRB* 83, 104504 (2011).

CDW: S Blanco-Canosa et al, PRB 90 054513 (2014)

YBCO phase diagram: comparison with CDW

Anisotropic Nernst effect in YBCO

Tc= 63 K – p=0.12 (twin free)

CDW: S Blanco-Canosa et al, PRB 90 054513 (2014)
Pseudogap? Mind the oxygen!......

Multi-band model

STM
IUC- charge order (Q=0)
Electronic nematic state

Fischer & Kim,
PRB 2011, PRB 2012
Davis & DH Lee

Polarized Neutron
IUC- magnetic order (Q=0)
Orbital magnetism

C.M. Varma,
PRB 2006

A.S. Moskvin,
JETP Lett. 2012

Spin-fermion model
(Sachdev, Chubukov, Efetov et al)

Quadrupolar Charge order
on CuO bonds
K. B. Efetov, H. Meier, and C. Pépin,
Nature Physics 2013
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HgBa$_2$CuO$_{4+x}$
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- Guichuan Yu, Yang Tang M. Greven (University Minnesota)
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La$_{2-x}$Sr$_2$CuO$_4$
- K. Conder, E. Pomjakushina (PSI) N. Christensen (Riso),
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Bi$_2$Sr$_2$CaCu$_2$O$_{8+x}$
- I. Laffez, F. Giovannelli (IUT-Blois, France),
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