Experimental report

21/10/2022

Proposal: **CRG-2776** **Council:** 4/2020

Title: Orbital magnetism in highly holde-doped two-leg ladder cuprates

Research area:

This proposal is a new proposal

Main proposer: **Dalila BOUNOUA**

Experimental team: Philippe BOURGES
Yvan SIDIS

Local contacts: Frederic BOURDAROT

Samples: Sr2Ca12Cu24O41
YBa2Cu3O6.6

Instrument	Requested days	Allocated days	From	To
IN22	8	8	22/09/2020	28/09/2020

Abstract:

Bi-axial magnetism in the pseudogap phase of $YBa_2Cu_3O_{6.6}$

1/ Scientific case

In the electronic phase diagram of high temperature cuprate superconductors (Fig. 1), the unconventional d-wave superconductivity (SC) emerges out of the mysterious pseudo- gap (PG) phase. One of the properties of PG state is that it exhibits discrete broken symmetries in the same region of the phase diagram over which a partial gap opens in the fermionic spectrum. The discrete broken symmetries are lattice rotation [1-4], interpreted in terms of an (Ising) nematic order, parity (*P*) [5] and time reversal (*T*) symmetry [6-9], usually interpreted in terms of loop Current (LC) order [10]. Since the lattice translation (*LT*) invariance is preserved, the Luttinger's theorem implies that none of these broken symmetries can induce the needed fermionic gap.

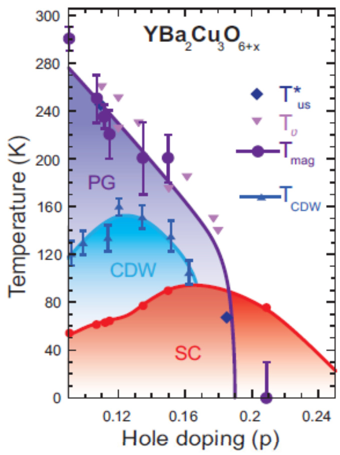

Figure 1: Phase diagram

An intra-unit-cell (IUC) magnetism that exhibits the same symmetry properties as the so-called LC phase, proposed by C.M. Varma in his theory of the PG [10] has been identified by PND in four cuprate families [11-13]. Considering the hole doping and temperature dependences of the PND signal [8-9,11-13], its specific location in momentum space and the fact that it fulfills the polarization sum rule [14-15], the existence of the IUC magnetism can be taken for granted. Such a LC state can also be described by a polar anapole vector [10-13]. However, the breaking of these discrete Ising-like symmetries cannot alone account for the opening of the PG. Alternatively, it has been proposed that a specific and coherent arrangement of fourfold-degenerated LC domains could lead at a superstructure, breaking the lattice translation invariance [14] giving rise to a magnetic response at finite wave vector.

2/ Experiment CRG#2776

This experiment was dedicated to the study of the low Q region in a detwinned $YBa_2Cu_3O_{6.6}$ co-aligned array of single crystals grown by the group of Pr. Bernhard Keimer (Max Planck Institute for Solid State Research, Stuttgart). The sample was aligned in the (100)/(001) scattering plane such that wave vector (H,0,L) were accessible.

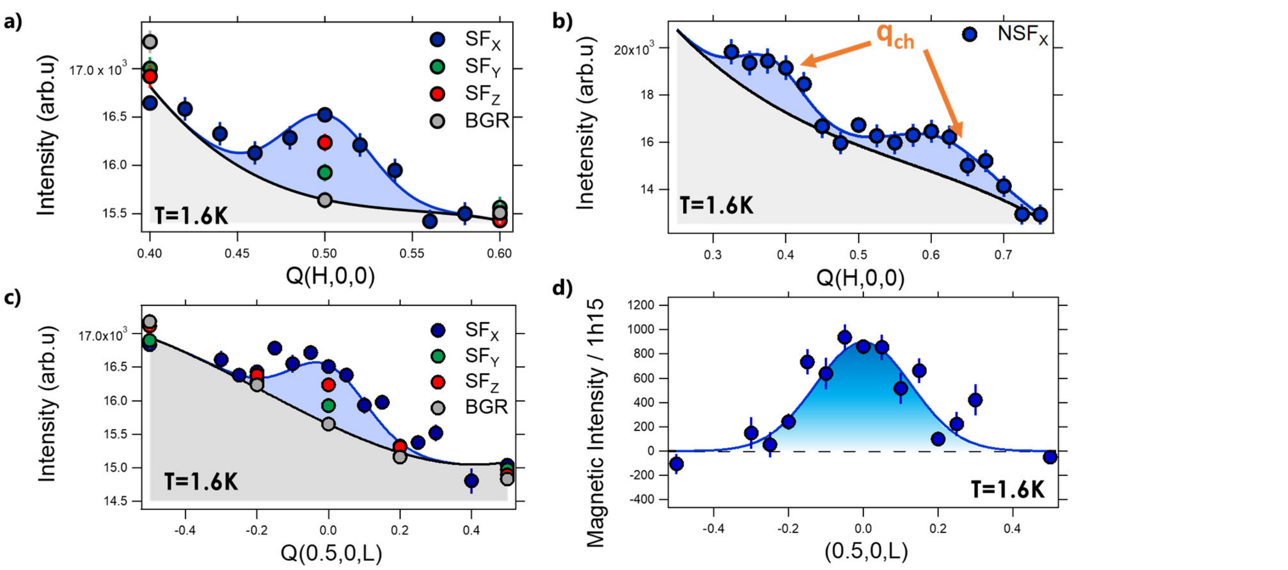

Figure 2. (a-b) Raw data scans along the (H,0,0) line in the YBCO-d sample in **(a)** the spin flip ($SF_{X,Y,Z}$) channel. The background (BGR) is extracted from XYZ-PA. **(b)** Same scan in the NSF_X channel indicating the CuO chains superstructure peaks at (q_{ch}). (c) Raw data scans along the (0.5,0,L) line in the spin flip ($SF_{X,Y,Z}$) channel. (d) Same scan as (c) with subtracted background as extracted from XYZ-PA. Lines are guide to the eye. The data were collected on the IN22-TAS.

The sample was installed into the orange cryostat dedicated to CRYOPAD. Elastic measurements were performed with a final neutron wave vector **k**f=2.662 Å^{-1}. A PG filter was inserted in the scattered beam to remove higher order contaminations.

Our measurements revealed a static magnetic response at the planar wavevector **q**=(0.5,0)≡($\boldsymbol{\pi}$,**0**) at low temperature as shown by the longitudinal H-scan in the SF_X channel (Fig.2.a). The same scan in the NS_{FX} channel (Fig. 2.b) reveals two nuclear peaks q_{Ch} = (H ± 0.125, 0, 0), inherent to the Ortho −VIII oxygen ordering of the CuO chains in that YBCO sample, which leads to a nuclear contribution where no magnetic signal occurs. The absence of magnetic scattering at the characteristic q_{Ch} positions confirms the CuO2 planes as the origin of the magnetic response at H = 0.5 [15]

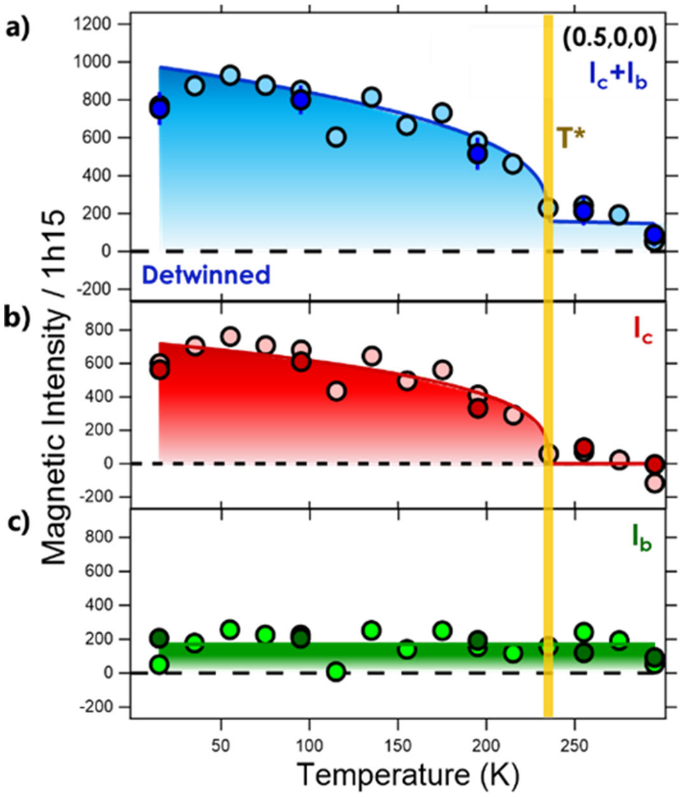

Figure 3. Temperature dependence of the biaxial magnetism in twin-free $YBa_2Cu_3O_{6.6}$ [15] measured at (0.5,0,0): (a) full magnetic scattering; (b) out-plane magnetic scattering ; c) in-plane magnetic scattering. Data collected on Thales TAS.

On cooling down from room temperature, the magnetic signal settles in at T* (Fig.3.a), the PG and IUC magnetism onset temperature (**Exp # 4-02-587 on Thales TAS**) highlighting that the **q**=0 and **q**=π magnetism may share a common origin. The orientation of the corresponding magnetic moment decomposes into a leading out of plane magnetic component (Fig.3.b) that follows an order parameter like temperature dependence and a flat in-plane magnetic component (Fig. 3c). The **q**=π magnetism remains at short range with correlation lengths of ~25Å in plane (about 5-6 unit cells) [15].

Our measurements further show that the magnetic correlations along the c-axis remain at short range with correlation lengths of ~13Å (Fig.2.c) representing the size of one unit cell along the c-axis [15].

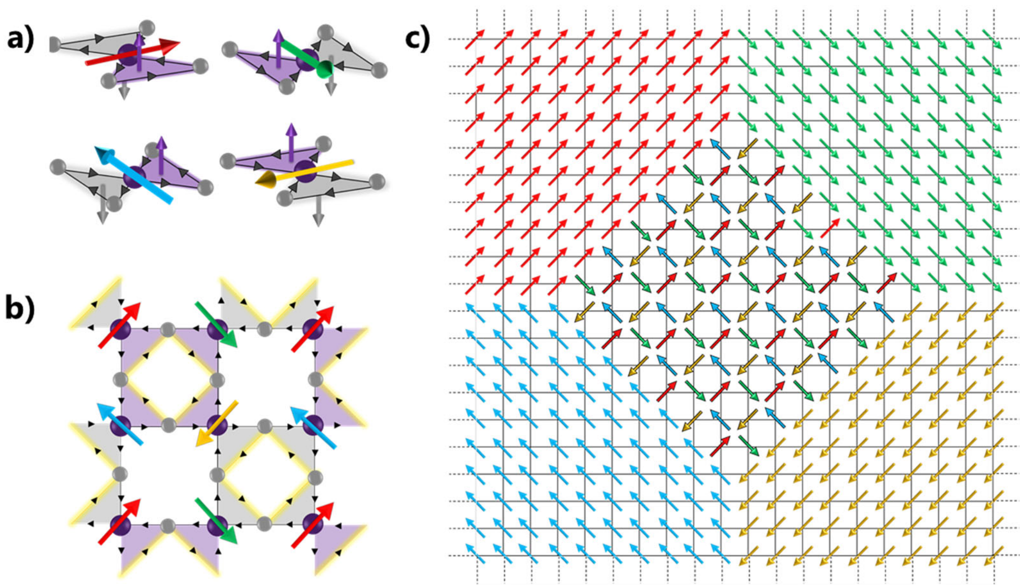

Figure 4. (a) Four possible degenerate ground states of loop currents (LCs). The grey and purple arrows represent magnetic moments along the c axis whereas the four other arrows represent anapoles carried by the LC state. (b) 2x2 LC pattern that can account for the **q**=π magnetism. (c) Example of 2D magnetic texture with 20x20 unit cells paved by anapoles (LC states). The central bubble with 2x2 LC patterns gives rise to the **q**=π short-range magnetism, whereas the **q**=0 magnetic signal arises from the larger color domains.[15]

Put together, the **q**=0 and **q**=π magnetic scattering observed by polarized neutron diffraction could actually belong to a unique complex magnetic texture of the CuO_2 unit cells hosting loop currents (Fig. 4. A-c). Such a magnetic texture would be made of 4 large ferro-anapolar domains with **q**=0 loop-current (LC) order (with LC patterns rotated by 90° from one domain to the next) and, at their corner, a bubble of intertwined LC forming a anapole-vortex like pattern, doubling the unit cell along both the a- and b-axis and leading to the **q**=π magnetic response . The existence of such a large supercell modifies the LT symmetry and can contribute to the PG. Indeed, such a magnetic texture is incommensurate and yields satellites at δ~1/2P away from **q**=0 and **q**=π, where 2P stands for the typical size of the supercell. Instrumental broadening along with a possible distribution of 2P throughout a crystal may then cause magnetic scattering centered at **q**~0.

3/ References

[1] R. Daou et al., Nature 463, 519 (2010)

[2] M.J. Lawler et al., Nature 466, 347(2010)

[3] Y. Sato et al., Nat. Phys. 13, 1074 (2017)

[4] H. Murayama et al., arXiv:1805,00276

[5] L. Zhao et al., Nat. Phys. 13, 250 (2017)

[6] A. Kaminski et al., Nature 416, 610 (2002)

[7] J. Xia et al., Phys. Rev. Lett. 100, 127002 (2008).

[8] B. Fauqué et al., Phys. Rev. Lett. 96, 197001 (2006).

[9] Y. Li et al, Nature 455,372, (2008)

[10] C. Varma, Phys. Rev. B 73, 155113 (2006)

[11] P. Bourges et al., C. R. Physique, 12, 461, (2011).

[12] Y. Sidis et al., Journal of Physics: Conference Series,449, 012012 (2013).

[13] P. Bourges et al., Comptes Rendus. Physique 22, 5 (2021).

[14] C. M. Varma, Phys. Rev. B 99 (2019), p. 224516

[15] D. Bounoua et al., accepted in Comm. Phys. arXiv:2111.005