Experimental Report

17/02/2015

Proposal: **4-01-1352** **Council:** 4/2014

Title: Search for new low energy magneticexcitations in superconducting cuprates

This proposal is a new proposal

Research Area: Physics

Main proposer: **MANGIN-THRO Lucile**

Experimental Team: MANGIN-THRO Lucile
SIDIS Yvan

Local Contact: STEFFENS Paul

Samples: $YBa_2Cu_3O_{6.85}$

Instrument	Req. Days	All. Days	From	To
IN20 CPA	14	13	20/11/2014	26/11/2014
			03/12/2014	10/12/2014
			10/12/2014	11/12/2014

Abstract:

The phase diagram of high-Tc superconductors is dominated by the mysterious pseudo-gap (PG) phase. Polarized neutron scattering studies in 3 different cuprate families, including $YBa_2Cu_3O_{6+d}$, highlighted the existence of an intra-unit-cell (IUC) order that develops when entering the PG state below T*. The observed magnetic signal displays similarities with orbital magnetic order predicted by the loop current theory. We have been recently able to prove the persistence of the magnetic IUC order in a nearly optimally doped $YBa_2Cu_3O_{6+d}$ sample. Furthermore, moving away from magnetic Bragg reflections, we could observe for the first time low energy magnetic excitations. These fluctuations are likely to be T-independent in the paramagnetic state as expected in Marginal Fermi Liquid Theory and then suddenly change below T* and Tc upon cooling down. Our discovery of new magnetic excitations in superconducting cuprates can open new routes for the understanding of the complex electronic properties of these materials. On the basis of such promising results, we would like to carry out a systematic study of their energy and moment dependencies as a function of temperature on IN20 with CRYPOAD.

ILL report on IN20 – nov.-dec. 2014
Search for new low energy magnetic excitations in superconducting cuprates
Lucile Mangin-Thro, Philippe Bourges, Yvan Sidis (LLB)
Local contact : Paul Steffens

The phase diagram of high temperature superconductors is dominated by a pseudo-gap (PG) phase with highly unusual physical properties [1]. Many theories attribute its origin to the proximity of a competing state, but there is a wide disagreement about the nature of this state. Beyond usual charge or spin instability, it has been proposed that the PG phase involves loop currents (LC) flowing around the CuO_2 square lattice with two loops per CuO_2 plaquette [2]. In the vicinity of each Cu site, LC generate staggered orbital magnetic moments and break time reversal symmetry, but preserve lattice translation invariance. Such an intra-unit-cell (IUC) magnetic order can be detected by polarized neutron scattering technique.

Using polarized neutron diffraction on the spectrometer 4F1 at Orphée Reactor at Saclay, we successfully reported the existence of a magnetic order in the PG state of 3 cuprate families: $YBa_2Cu_3O_{6+x}$ (Y123) [3-4], $HgBa_2CuO_{4+d}$ (Hg1201) [5], $Bi_2Sr_2CaCu_2O_{8+d}$ (Bi2212) [6]. The change of the magnitude of the observed effect with different neutron polarization [7] demonstrates the magnetic nature of the phenomenon, and rules out an experimental artifact. The observed symmetry is consistent with the theoretically-predicted broken-symmetry state, LC phase [2]. The IUC order develops below a temperature T_{mag} that matches the PG temperature T* as defined by the resistivity measurement for all families of compounds. Our systematic study, carried on many single crystals with various hole doping levels demonstrates that the existence of an IUC magnetic state is a genuine properties of the PG phase of superconducting cuprates. Moreover, our polarized neutron scattering measurement suggests that the PG phase is a symmetry breaking state, a conclusion which is now corroborated by ultrasound measurements [8].

Around optimal doping (p=0.16), where the SC transition is maximum, the magnetic critical temperature as well the magnetic intensity are reduced as one approaches the quantum critical doping [2,7] (p_c~0.2), where the PG state vanishes according to thermodynamic measurements. Even using polarized neutron diffraction, the observation of the static magnetic signal is difficult. In $YBa_2Cu_3O_{6.85}$ (T_c=89 K, p~0.15), we have been recently able to observe the IUC magnetic order that develops in this sample at T_{mag} ~200 K. Combining polarized neutron measurements on 4F1 and D7, the 3D magnetic correlations appears to develop at short range only (ξ_{ab}~20a) [9]. Moving away from the Bragg reflection (1,0,0), we could observe for the first time low energy magnetic excitations. First measurements with inelastic polarized neutron performed at Q=(0.9,0,0) and -4meV, on 4F1 (LLB, k_i=2.57Å^{-1}), revealed after polarization analysis a low energy magnetic signal, which is likely to change upon cooling down, first below T_{mag} (=T*) and then below T_c.

Our goal was then to characterize the low energy magnetic excitations as a function of temperature T, energy E and momentum Q. In a second experiment, we tried to study these magnetic excitations at lower energy on IN14 (ILL, k_f=1.5Å^{-1}), but the magnetic signal intensity was unfortunately too weak to be unambiguously identified with these experimental conditions. From this experiment we deduce that a thermal spectrometer should be more suited for the observation of these fluctuations. We then performed a pilot experiment on thermal TAS 2T (LLB, k_f=2.662 Å^{-1}). At room temperature, the new spin excitations are clearly visible from -8 to 8 meV, and it was hard to tell if it was present at higher energies. Further studies performed on 4F1 at -4meV showed that their momentum dependence suggest that there are weighted by a magnetic form factor decreasing faster than the Cu magnetic form factor, in agreement in the LC theory. However, we still ignore whether the magnetic intensity vanishes when |Q| goes to 0, as expected for LC.

To go further, we have performed a 14-days experiment on the high flux spectrometer IN20 (flux twice better than on 2T and 3 times compared to 4F1) to study these new magnetic excitations found in our $YBa_2Cu_3O_{6.85}$ single crystal. The sample was aligned in a way to access wave vectors Q=(H,0,L). The measurements was carried out at k_f=2.662 $Å^{-1}$ for low energies or 4.1 $Å^{-1}$ for higher energies. We used a Heusler analyzer and CRYOPAD was necessary to improve the polarization measurements and to prevent us from depolarization of the neutron beam in the SC state.

With this experimental set-up, we mostly studied the T-dependence of the low energy magnetic excitations at Q=(0.9,0,0) for different energies.

We started with an energy scan to determine which energies were interesting to study. Figure a shows the E-dependence of the magnetic signal, extracted from polarization analysis, measured at room temperature T=300K for Q=(0.9,0,0). The signal seems to be centred around 0meV with an energy range of about +-8meV (which is in agreement with our 2T measurements) and a possible increase at higher energies is suggested. We choose to study the T-dependence of the magnetic signal, from 300K to 10K, at Q=(0.9,0,0) for several energies : 19meV (fig. b), 6meV, 2meV (fig. c) and 0meV (fig. e). The 6meV study was not conclusive, we did not count enough long. The counting time presented in the figures is about 4/5h per point. Both 19meV and 2meV T-dependences (fig. b-c) show a bump around T_{mag} and a peak of intensity below T_c. The magnetic intensity is stronger at lower temperature. At fixed energy and temperature, we also performed a few rocking scans, namely Q-scans with |Q| constant. For instance, figure d presents for 2meV at 75K the Q-dependence of the peaked intensity seen at low temperature. It seems to go to lower intensity at low Q but our lack of statistics disable us to conclude about the momentum dependence.

The last figure, fig. e, shows the T-dependence of the magnetic signal measured at E=0meV for Q=(0.9,0,0). These data are compared and in agreement with our measurements first done on 4F1 (LLB). A strong enhancement of the magnetic intensity upon decreasing the temperature appears for elastic measurements. It appears that the low temperature magnetic signal becomes stronger upon approaching elastic position.

Finally, all the data we get during this experiment is in agreement with what we observed previously at LLB and provided new insight about the low energy magnetic excitations. Among all what was observed in these (in)elastic measurements, the most striking feature comes from the low temperature magnetic signal especially at 0meV. This study appeals for more work on the elastic part.

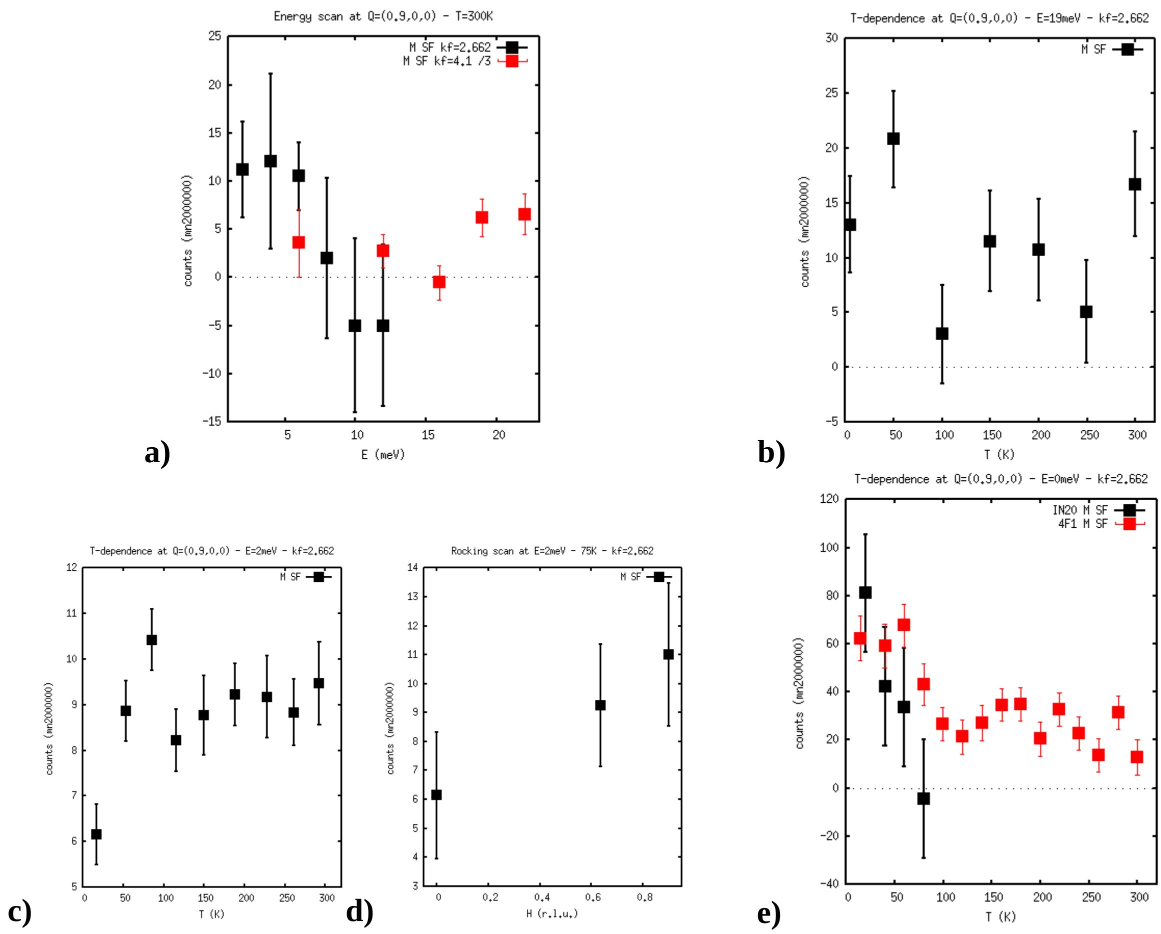

Figure. **a)** E-dependence of the magnetic signal measured at room temperature T=300K for Q=(0.9,0,0). **b)** T-dependence of the magnetic signal measured at E=19meV for Q=(0.9,0,0). **c)** T-dependence of the magnetic signal measured at E=2meV for Q=(0.9,0,0). **d)** Q-dependence of the magnetic signal measured at E=2meV and T=75K. **e)** T-dependence of the magnetic signal measured at E=0meV for Q=(0.9,0,0). Data are compared to measurements performed on 4F1 (LLB).

In all panels, the magnetic signal is extracted from polarization analysis.

References:

[1] M. R. Norman and C. Pepin, *Rep. Prog. Phys.* **60**, 1547 (2003)
[2] C.M. Varma, *Phys. Rev. B* **73**, 155113 (2006)
[3] B. Fauqué et al, *Phys. Rev. Lett.* **96**, 197001 (2006)
[4] H. Mook et al, *Phys. Rev. B* **78**, 020506 (2008)
[5] Y. Li et al, *Nature* **455**, 372 (2008)
[6] S. De Almeida-Didry et al, *Phys. Rev. B* **86**, 020504 (2012)
[7] P. Bourges and Y. Sidis, *C. R. Physique* **12**, 461 (2011)
[8] A. Shekhter et al, *Nature* **498**, 75 (2013)
[9] L. Mangin-Thro et al, arXiv:1501.04919