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Superconductivity, pseudo-gap, and stripe correlations in high-T_c cuprates

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Abstract

Under-doped La-214 cuprates show a charge- and spin-modulation known as "stripes" [1]. These stripe modulations are (quasi)-static close to 1/8 hole doping where superconductivity is suppressed. The pseudo-gap phase of other cuprate compounds recently also revealed charge modulation, but interpreted rather as a charge density wave (CDW) [2, 3, 4], that possibly competes with superconductivity. In this context, to better understand the interplay between the stripe phase and the superconductivity, we use angle-resolved photoemission spectroscopy to study the electronic band structure and gap in La-214 cuprates near 1/8 doping ($La_{2-x-y}Nd_ySr_xCuO_4$ (x = 0.12; y = 0.0 & 0.4)) and compare with the previous results in the same system [5] and $La_{1.86}Ba_{0.14}CuO_4$ [6]. Our data shows a loss of spectral intensity towards the end of the Fermi arcs, that is possibly due to a strong renormalisation, as already pointed out elsewhere

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[5], with a noisy but still measurable gap. On the nodal direction no gap is observed within our statistics, but a sizeable decrease in intensity with temperature. Moreover, we do not see any shadow band, but our Fermi surface can be well modelled with a single electron band calculation in the tight binding approximation, even very close to the 1/8 doping $La_{2-x-y}Nd_ySr_xCuO_4$ with and without Nd substitution.

Keywords: cuprates, superconductivity, pseudo-gap, ARPES, stripes, Fermi surface

1. Introduction

The nature of the normal-state gap (pseudo-gap) and its relationship with superconductivity are believed to hold the key for understanding the mechanism of high-T_c superconductivity. In cuprates, the pseudo-gap opens well above the superconducting critical temperature at moderate doping. Many previous experiments suggest that the pseudo-gap is distinct from superconducting gap and that it opens towards the anti-nodal direction, similar to a *d*-wave symmetry. A large body of experimental evidence now suggests that, at least in a small region of the under-doped phase diagram, there is a broken-symmetry state that is distinct from homogeneous superconductivity. In the "214 family", the low temperature phase is accompanied by the ordering of charge and spin in a stripe form, where a fraction of carriers forms a charge modulation coexistent with spin modulation in a configuration which is referred to as stripes [7, 8]. Charge-modulations have been proposed as a possible origin of the broken-symmetry state, either in the stripes [1] or the CDW [9] form. In the region of the phase diagram where these charge-modulations are static, scattering experiments have suggested that they compete with superconductivity [2, 3, 4], although a possible different role of the fluctuating stripes is still debated [1]. We can pin the fluctuating stripes in $La_{2-x}Sr_xCuO_{4+\delta}$ (LSCO) at x = 1/8 doping, by replacing Sr with Ba in $La_{2-x}Ba_xCuO_{4+\delta}$ (LBCO), or with partial substitution of Nd on the La site in $La_{2-x-y}Nd_ySr_xCuO_{4+\delta}$ (LNSCO). Then the charge ordering

in LBCO or LNSCO is static and suppresses superconductivity in a narrow doping region around x = 1/8 [10]. When lowering the temperature, the pinning first appears for the charge component, accompanied by a structural transition from the low temperature orthorhombic (LTO) phase to the low temperature tetragonal (LTT) phase below T_{LTT}. Lowering the temperature even further, the magnetic component is pinned as well below T_{stripe}. In LSCO, as the charge/spin modulation static component is null [7] or much weaker [11], the impact of the density modulation is mitigated, causing only a slight depression in T_c in the vicinity of x = 1/8 [12] doping.

The link between the anti-nodal pseudo-gap and charge modulations (CDW/stripe phase) is explored by C. Matt and co-workers with an angle-resolved photoemission spectroscopy (ARPES) study of the charge stripe ordered system $La_{1.6-x}Nd_{0.4}Sr_xCuO_4$ at 1/8 doping [5]. More recently, the nature of the pseudo-gap close to the node has been investigated in the 214 LSCO system, but without charge modulation pinning and for low doping [13]. The authors show a link between a spin density wave and the nodal gap. In this work, we report ARPES results for the nearly 1/8 doped $La_{1.88}Sr_{0.12}CuO_4$ and $La_{1.48}Nd_{0.4}Sr_{0.12}CuO_4$ in order to study the nature of the pseudo-gap and its relationship with superconductivity, as well as its possible link to the spin/charge modulations.

2. Methods and experimental details

High-quality single crystals of nearly 1/8 doped $La_{1.88}Sr_{0.12}CuO_4$ and $La_{1.48}Nd_{0.4}Sr_{0.12}CuO_4$ were grown from the melt in an image furnace by the travelling solvent floating zone (TSFZ) method under a pressure of 3 bar oxygen at the ICMMO, Orsay. The T_c were measured and determined from the susceptibility measurement by the MPMS (QuantumDesign) SQUID magnetometer available at the MPBT facility of the UPMC University (Paris, France), shown in Figure 1 (a) and 1 (b). The onset temperatures of the superconducting transition T_c are 31 K for LSCO and 4.6 K for LNSCO, respectively. The structural and magnetic

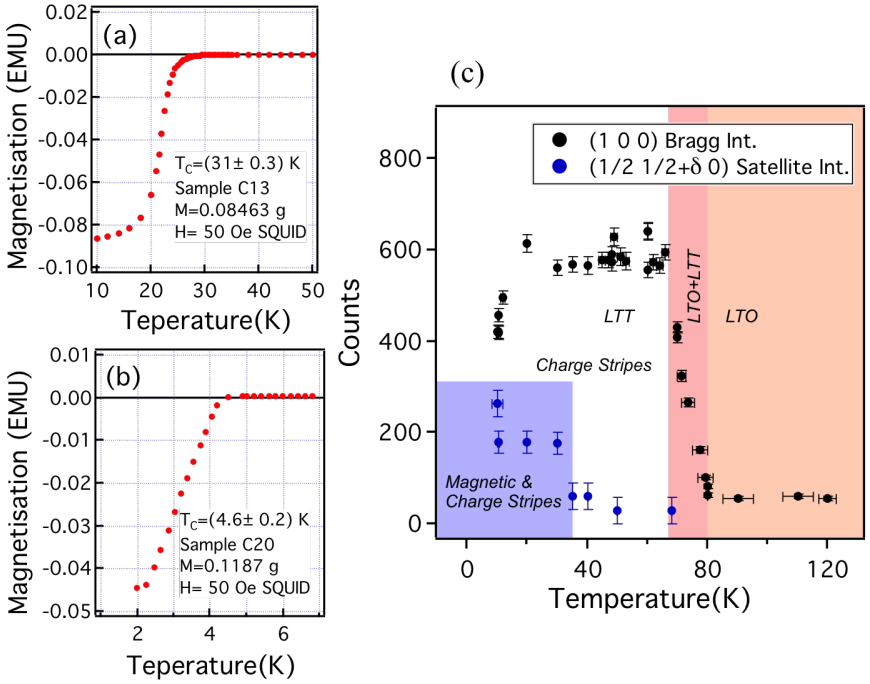


Figure 1: (Color online). The magnetisation measurements of (a) $La_{1.88}Sr_{0.12}CuO4$ (sample C13) and (b) $La_{1.48}Nd_{0.4}Sr_{0.12}CuO_4$ (sample C20). Temperature dependence of the magnetisation under a field of 50 Oe for the zero-field cooled condition. (c) Phase diagram of $La_{1.48}Nd_{0.4}Sr_{0.12}CuO_4$ determined by neutron scattering data: the temperature dependence of the super-lattice peak intensities. Blue filled circles: magnetic superlattice peak at the (1/2, 1/2+δ, 0), $\delta \sim x \sim 0.111$; Black filled circles: (1, 0, 0) structural peak allowed only in the LTT phase.

stripes characterisation was made using the 1T 3-axes spectrometer, run by KIT (Karlsruhe, Germany) and the LLB laboratory (Ce-Saclay, France) available at the Orphee neutron source (CE-Saclay, France), in particular to measure T_{LTT} and T_{stripe}. In Figure 1 (c), we also show the neutron scattering data on the LNSCO sample. We observe the intensity of the Bragg reflection (1, 0, 0), which is forbidden in the LTO phase yet allowed in the LTT phase, increases at $\sim$ 80 K and saturates at $\sim$ 70 K. At this temperature, the charge modulations (stripes) are known to appear [7]. Below 35 K, we observe additional intensity on the satellite of the magnetic Bragg reflection at (1/2, 1/2+δ, 0) due to scattering from the magnetic stripes. Therefore, we can identify four different phases in this LNSCO composition with three transition temperatures: a superconducting state below $T_c \sim 4.6$ K, magnetic stripes state below $\mathrm{T_{stripe}} \sim 35$ K, LTT phase below $\mathrm{T_{LTT}} \sim$ 70–80 K and finally an LTO phase above $\mathrm{T_{LTT}}$.

The ARPES measurements were performed on the CASSIOPEE-B-ARPES beamline of the Synchrotron SOLEIL (Ormes de Merisier, France). This beamline has the necessary energy and momentum resolution, photon energy, and temperature ranges to allow a fast and systematic exploration of the experimental phase space. The crystals were cut from a larger bar, at a given orientation determined by Laue diffraction in order to fit the cryostat holder. A notch was added to guide the cleave parallel to the *ab*-plane as much as possible. The crystals were mounted on the rotating head of the cryostat and cleaved in-situ at 10^{-11} mbar and 9 K. In this work, we performed our ARPES measurements of the LNSCO sample at three different temperatures (T = 9 K, 55 K and 90 K), to investigate the magnetic stripe phase, charge-only stripe phase, and the normal phase.

3. Results and discussion

Figure 2 (a) shows a well-defined Fermi surface of LSCO for the compound x = 0.12 obtained at T = 5 K in the superconducting states reconstructed from experimental ARPES data measured at 5 K with a photon energy of $\hbar\omega = 55$ eV,

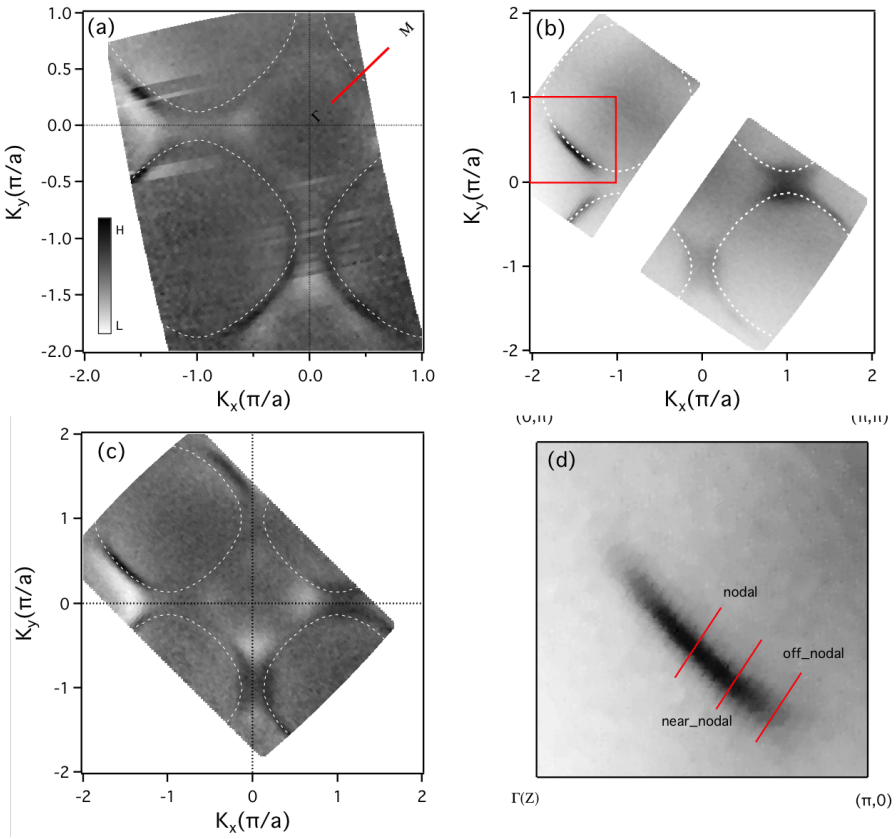


Figure 2: (Color online). Angle-resolved photoemission spectra and the Fermi surface of LSCO and LNSCO. (a) The Fermi surface of $La_{1.88}Sr_{0.12}CuO_4$ (LSCO) with a large momentum coverage measured at a photon energy of $\hbar\omega = 55$ eV at T = 5 K (below T_c). The dashed curves represent the tight binding Fermi surface results from a global fit to the data as guide to the eye. (b) The same as (a) but at T = 55 K (above T_c) (c) The Fermi surface of $La_{1.48}Nd_{0.4}Sr_{0.12}CuO_4$ at T = 9 K. (d) Zoom of the section marked in red in pane (b) showing the dispersion cuts along the Fermi surface.

which represents the integrated photoelectron intensity of spectra over a small energy window $E = E_F \pm 10$ meV, normalised using the intensity well above E_F. The normal states Fermi surface are shown in Figure 2 (b) for LSCO and 2 (c) for LNSCO. The Brillouin zone guidelines shown in Figure 2 (a) are drawn by ignoring the finite k_z dispersion in the system, as this is indiscernible within the experimental accuracy for the photon energies used. We see a hole-like Fermi surface with a large pocket centred at M (π, π), which is consistent with previous observations in under-doped cuprates. Similar to the Ref. [14], we do not see the shadow bands previously reported in 1/8 doping, which potentially represents additional ingredients in the band structure that goes beyond the single-band picture. Indeed, it has been suggested that the shadow band intensity could be even enhanced at x = 1/8 compared with both its lower and higher doping sides [15]. Our data roughly corresponds to what expected from single electron bands calculations in the tight binding approximation (white, dashed line in Figure 2 (a)).

In Figure 3, we compare the spectral line shapes of the nodal and off-nodal cuts (depicted in Figure 2 (d)) on LSCO samples in the superconducting states and in the normal states. In panel (a), the energy distribution curves (EDCs) integrated over a small interval of 0.02 Å around k_F were obtained along the nodal and off-nodal directions, both below and above $T_c = 31$ K. We can see a discernible quasi-particle peak in the superconducting state as well as in the normal state in the nodal region. In the off-nodal region, in contrast, the spectral weight near E_F is suppressed both below and above T_c, as already reported in the region where the pseudo-gap is open [5, 14] . There is no measurable spectral weight difference between data below and above T_c. In order to estimate the size of the energy gap at each k_F, we symmetrised the ARPES spectrum with respect to E_F to eliminate the effect from the Fermi-Dirac function [16], and the E_F-symmetrised EDCs are shown in panel (b) and (c). We can observe that, for the LSCO (x=1/8) sample, the superconducting gap is opening when we move from the nodal to the off-nodal region at T = 5 K, and persists at T = 55 K, well above T_c, where an almost comparable gap at the off-nodal region is clearly

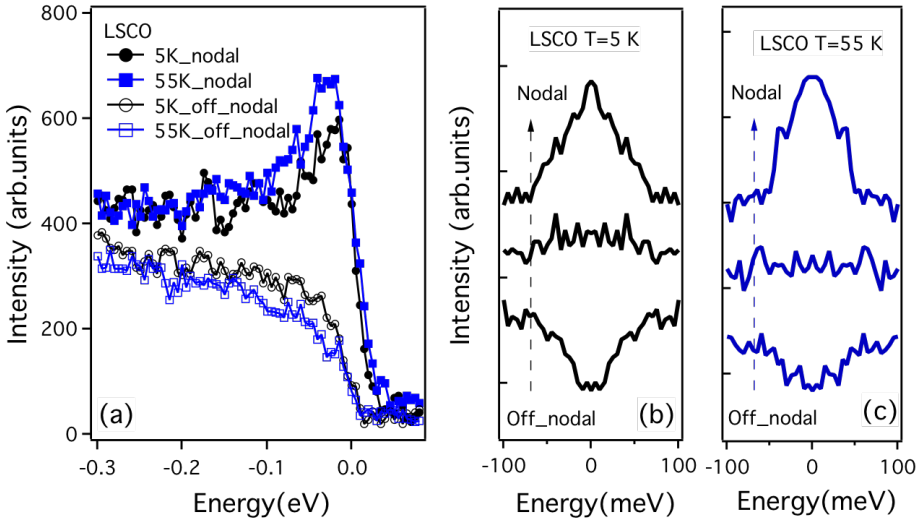


Figure 3: Superconducting gap and pseudo-gap measured by ARPES. (a) Comparison of energy distribution curves (EDCs) at k_F along the nodal/off-nodal directions below and above T_c for $La_{1.88}Sr_{0.12}CuO_4$. (b) and (c) The E_F-symmetrised EDCs from the nodal to off-nodal region obtained at T = 5 K and T = 55 K, respectively.

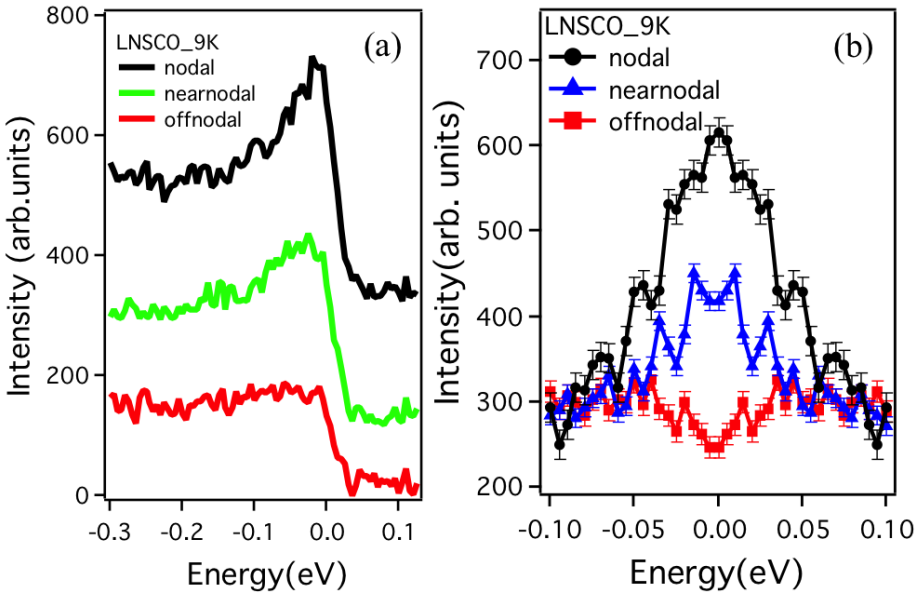


Figure 4: (a) Temperature and momentum dependence of EDCs at 9 K. (b) EDCs of panel (a) symmetrised.

visible, as expected for a pseudo-gap. The spectral evolution with temperature, shown in Figure 3 (c), indicates that the off-nodal pseudo-gap persists deep into the LTO phase. Our observation is consistent with the report of Ref. [17], which also shows that a off-nodal pseudo-gap exists at the 1/8 doping.

In order to see the pseudo-gap in the 1/8 doped LNSCO, we show in Figure 4 (a) the EDCs for several cuts in the reciprocal space at T = 9 K, from nodal region to off-nodal region. The EDCs show a fairly weak quasi-particle peak with a high background level along the off-nodal direction. When moving towards the nodal direction, the quasi-particle peak intensity evolves and gets sharp. This evolution of the quasi-particle peak as function of k-momentum is consistent with general observations: the spectral weight has a maximum near the node and drops off rapidly when approaching the antinode where it is suppressed and finally vanishes, resulting in a broad line-shape with a weak shoulder near E_F. Despite the evolution of the low-energy spectral weight along the Fermi

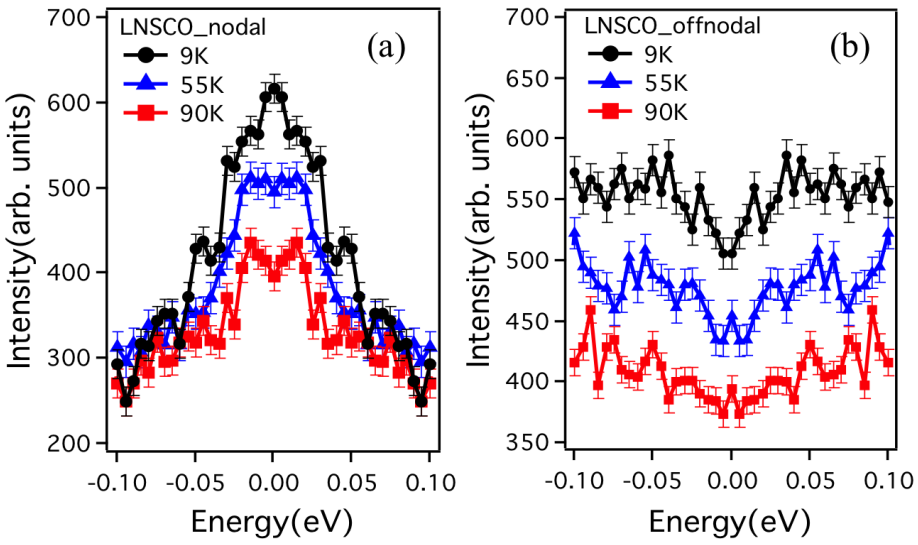


Figure 5: (Color online). Temperature evolution of the nodal pseudo-gap (a) and off-nodal pseudo-gap (b) on 1/8 doped LNSCO shown as symmetrised EDCs.

surface, the quasi-particle peak maintains a distinct structure in momentum space, which gives the possibility to determine the peak position. For example, as shown in Figure 4 (a), we easily see that the peak position tends to move towards higher binding energy indicating an opening of the pseudo-gap with a maximum at the off-node. The raw symmetrised EDCs of LNSCO are shown in Figure 4(b). We can see the opening of the pseudo-gap as the momentum cut goes from the nodal direction towards the off-nodal region at the end of the Fermi arc.

The temperature evolution of the two momentum cuts along the nodal and off-nodal direction are shown in Figure 5, in symmetrised EDCs. In Figure 5 panel (a), despite the very noisy data, a small gap could be seen above 55 K, which would confirm the data shown by Matt and coworkers [5]. This suggests that the pseudo-gap can exist in the nodal region, but would require further measurements in order to have sufficient statistics to confirm the result.

4. Conclusions

Our data shows a loss of spectral intensity towards the end of the Fermi arcs, that is possibly due to a strong renormalisation, as already pointed out elsewhere [5], with a noisy but still measurable gap. On the nodal direction no gap is observed within our statistics, but a sizeable decrease in intensity with temperature. Moreover, we do not see any shadow band, but our Fermi surface can be well modelled with a single electron band calculation in the tight binding approximation, even very close to the 1/8 doping, both for LSCO and Nd substituted LNSCO.

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