Exploring whether a spin density wave (SDW) is responsible for the charge excitations gap in the high-temperature superconducting cuprates is difficult, since the region of the phase diagram where the magnetic properties are clearly exposed is different from the region where the band dispersion is visible. On the one hand, long range magnetic order disappears as doping approaches 2% from below, hindering our ability to perform elastic neutron scattering (ENS). On the other hand, cuprates become insulating at low temperature when the doping approaches 2% from above, thus restricting angle-resolved photoemission spectroscopy (ARPES). In fact, ARPES data for samples with doping lower than 3% are rare and missing the quasiparticle peaks in the energy distribution curves (EDCs) \(^{[1]}{[2]}\). The main problem is the high resistivity of extremely underdoped samples, which is detrimental to ARPES due to charging effects. Nevertheless, the resistivity of \(\text{La}_{2-x}\text{Sr}_x\text{CuO}_4\) (LSCO) as a function of temperature, at 2% doping, has a broad minimum around 100 K \(^{[3]}\). This minimum opens a window for both experiments. By preparing a series of LSCO single crystals with ~0.2-0.3% doping steps around 2%, we managed to find one to which both techniques apply. This allows us to explore the cross talk between the magnetic and electronic properties of the material.

The series of samples are first characterized by muon spin rotation (\(\mu\)SR). In Fig. 1a we show the muon spin rotation frequency as a function of temperature for all the crystals. In samples with doping equal to or less than 2%, the oscillation starts at temperatures on the order of 100 K. At 2%, there is a sharp transition from the antiferromagnetic long range order to the spin glass state where the same oscillations appear only at temperatures on the order of 10 K \(^{[4]}\). More details of the \(\mu\)SR characterization of the samples are given below and in the supplementary material. We perform the ENS and ARPES measurements on a sample with \(x = 1.92\%\) (red rhombuses) which is antiferromagnetic with a Néel temperature \(T_N = 140\) K. Fig. 1b shows the ARPES intensity map near the Fermi level \((E_F)\) in the second Brillouin Zone (BZ), measured along cuts parallel to cut 1 and 2 shown in the figure. The high intensities represent the underlying Fermi surface (FS) and has the morphology of the FS in more doped LSCO \(^{[5]}\) and other cuprates. Most of the intensity is centered around the zone diagonal. This suggests the presence of gapped electronic excitations in the off-diagonal \((0,\pi)\) region. Similar results were obtained at a higher doping level of \(x = 3 - 8\%\) \(^{[6]}\).

Figure 1c depicts ENS for the same sample at 3 K. The scans are performed in a narrow range in the reciprocal lattice space centered around the \((1, -1)\) point, in the standard tetragonal ARPES units of \(\pi/a\). The scanned area of the ENS experiment is presented on the BZ of the ARPES experiment by the small inset in Fig. 1b. Two incommensurate peaks are present in the center of the figure. Such incommensurate peaks occur when, on top of the main magnetic order, the system develops spin modulations (stripes) running in diagonal to the bond directions (diagonal stripes). The stripes and commensurate scattering observed in our sample are in agreement with previous reports for low doping LSCO \(^{[7]}{[8]}\), and are discussed further below.

In Fig. 2a-h, we show the temperature dependence of ARPES data in the vicinity of point III along cut 3 in Fig. 1b. All spectra are divided by resolution broadened Fermi-Dirac distribution at the nominal temperature. Data analysis by the Lucy–Richardson deconvolution method \(^{[9]}\) is discussed in the supplementary material. At high temperatures \((T > 50\) K\) the dispersive peak crosses \(E_F\) as clearly seen in Fig. 2a. In contrast, at low temperatures \((T < 45\) K\) there is a gap in the electronic spectra, i.e. the peak position at \(k_F\) stays below \(E_F\). A similar gap exists in LSCO up to 8% doping \(^{[9]}\), in \(\text{LBCO}\) at 4% \(^{[10]}\), in the electron doped compound \(^{[11]}\), and in \(\text{Bi}_2\text{Sr}_2\text{Ca}_2\text{Cu}_2\text{O}_8\) \(^{[11]}\), and also in simulations where inhomogeneous SDW and superconductivity coexist \(^{[12]}\). EDCs extracted from Fig. 2a-h, at \(k_F\) given by point III of Fig. 1b, are plotted in Fig. 2i. The solid lines are guides to the eye. At temperatures above 45 K, the peak is at \(E_F\). However, below this temperature the peaks are clearly below \(E_F\), indicating the presence of a gap. Another important aspect of these EDCs is the fact that at all low temperatures, \(E_F\) is not in the middle of the gap, namely, the intensity of the spectra immediately above \(E_F\) is lower than at \(E_F\). This could be an analysis artifact due to the division by the resolution broadened Fermi-Dirac function \(^{[13]}\) or indicate that the particle-hole symmetry is broken. Particle-hole asymmetry toward the diagonal region in the non-superconducting phase \(^{[14]}\), and in the
FIG. 1: (a) muon spin rotation frequency as a function of temperature for LSCO single crystals with different \(x\) values. At \(x = 2\%\) there is a clear transition from an antiferromagnetic to a spin-glass ground states. The data in the rest of this paper is from the \(x=1.92\%\) sample which is in the antiferromagnetic phase. (b) Low energy ARPES data in the second Brillouin Zone. The red lines 1, 2 show cuts on which data was collected. Line 3 is the cut on which temperature dependence data is presented in Fig. 2. Point I, II, and II mark points where EDCs are extracted. The intensity is centered in the diagonal region. The inset at \(k = (1, -1)\) is an illustration of the location of the commensurate and incommensurate magnetic peaks. (c) Elastic neutron scattering measurements at 3 K around a magnetic reciprocal lattice vector showing two incommensurate peaks. The red lines depicts the measurements scan direction.

FIG. 2: (a-h) ARPES spectra along a cut given by line 3 in Fig. 1. The spectra are divided resolution broadened Fermi-Dirac distribution. At high \(T\) the spectrum crosses the Fermi energy. At low \(T\) it does not. (i) EDCs at the Fermi momentum of point III in Fig. 1b for different temperatures. The solid lines are guides to the eye. At 10K the peak is clearly below the Fermi energy. \(\Delta(T)\) is presented in Fig. 4c. (j) MDC at \(E_F\) as a function of temperature showing that \(k_F\) in the diagonal region is temperature independent.
off-diagonal region [15], was found previously. However, it is very difficult to distinguish between the two options in our sample with extremely low carrier concentration.

Another parameter relevant for understanding the mechanism by which this diagonal gap opens is the temperature dependence of $k_F$. This is explored by extracting the momentum dispersion curve (MDC) at $E_F$ from Fig. 2a-h, as presented in Fig. 2j. The peak position fluctuates somewhat around a constant value as the temperature is lowered, indicating that $k_F = 0.63(\pi/a)$ along the diagonal is temperature-independent. Therefore, the high intensity curves in Fig. 1b represents the FS.

The evolution of the gap around the FS is shown in Fig. 3a-b for 10 and 100 K. The spectra marked I and II in Fig. 3a are EDCs at the $k_F$ of points I and II in Fig. 1b. The spectrum in between correspond to $k_F$ between point I and II. EDCs shown in Fig. 3b are from similar point along the FS. In the off-diagonal region, there is no spectral weight at $E_F$ for both temperatures, indicating that the off-diagonal gap opens at a temperature higher than 100 K. In the diagonal region, there is high spectral weight at 100 K, but not at 10 K. Thus at 100 K we observe a Fermi arc [14], while at 10 K a gap appears all around the FS.

Finally, in Fig. 4 we present a summary of parameters extracted from all three techniques. Fig. 4a shows the temperature dependence of the muon rotation frequency and magnetic volume fraction. The inset represents a fit of a three-component model, with one frequency, to the $\mu$SR data at different temperatures. Very similar gap values are found using the Lucy–Richardson de-convolutions method (see supplementary material) [9]. The gap opens at 50 K. The major observations in this figure are: I) the diagonal gap opens only when the commensurate moment is nearly at its full value. II) the diagonal gap opens when the incommensurate moment is not detectable by ENS.

On the basis of weak coupling theory, Berg et al. [19] argued that the commensurate part of the SDW can open a diagonal gap only if the moment is larger than a critical value. However, the opening of the gap will be accompanied by a shift in $k_F$. The effect of the incommensurate part of the SDW depends on the properties of time reversal followed by translation symmetry, which can be broken or unbroken. In the unbroken case a nodal gap will open when the perturbation exceeds a critical value. Both these options do not agree with our data. In the broken symmetry case, a nodal gap can open for arbitrarily small perturbation with no impact on $k_F$. This option is in agreement with our measurements and bares important information on the symmetries of the ground

![Figure 3: (a) EDCs at different $k_F$ along the FS in two different temperatures. The fermi surface angle $\phi$ is indicated above each EDC. Spectra I and II are taken at the $k$ of point I and II in Fig. 1b which are defined by the crossing point between the red lines 1 and 2 and the FS. The other EDCs are from the crossing points in between. At 10K a gap is observed all around the FS. $\Delta(\phi)$ is presented in the inset of Fig. 4c. (b) Similar EDCs at 100 K. In this case a gap is observed only in the off diagonal region.](image-url)
FIG. 4: A summary of experimental parameters from all three techniques. (a) Muon rotation frequency and the magnetic volume fraction of the sample as a function of temperature taken from a fit to a three Lorentzians model (see supplementary material). The inset shows raw data and the fit quality for the x=1.92% sample. (b) Commensurate and incommensurate elastic neutron scattering intensity. The inset is the raw data and the fit quality for the x=1.92% sample. (c) ARPES diagonal gap $\Delta$ at $k_F$, as obtained from the peaks in Fig. 2i, versus temperature. The inset shows the angular dependence of the gap $\Delta(\phi)$.

state. Another possibility is that the gap is of the superconducting type, which maintains particle-hole symmetry and keeps $k_F$ fixed. This option would mean that the cuprates have a superconducting gap in the AFM phase.

To summarize, we detect a nodal gap in the AFM phase of La$_{2-x}$Sr$_x$CuO$_4$. The gap opens well below $T_N$ and a bit above the temperature where incommensurate SDW is detected. This finding puts strong restrictions on the origin of the nodal gap.

I. SUPPLEMENTARY MATERIAL

A. $\mu$SR

The experiment was carried out at PSI on the GPS beam line. We fit the muon polarization as a function of time to

$$P_\mu(t) = (1 - V_m) e^{-\frac{1}{2} D t^2} + V_m \left[ p e^{-(R_1 t)^{b_1}} + (1 - p) e^{-(R_2 t)^{b_2}} \cos(\omega t + \phi) \right] + P_{BG}$$

where $\omega$ is the muon rotation angular frequency, $V_m$ stands for the magnetic volume fraction, $p$ is the amplitude of the rotating signal resulting from the angle between the muon spin and the internal field, $D$, $R_1$ and $R_2$ are relaxation rates, $b_1$ and $b_2$ are stretching exponents, and $P_{BG}$ is the background polarization from muon that missed the sample. We could fit the data well with $b_1 = 0.5$ and $b_2 = 1$ for most of the temperatures. Between $T = 25$ K to 50 K we allowed freedom in their values to achieve an optimal fit.

B. ARPES

The experiment was done in PSI using conditions similar to those in Ref. [20]. Charging tests have been carried out by varying the photon flux. No charging was found. In addition, after performing the high temperature measurements, the sample was cooled again and the results at 10 K were reproducible. We examined the surface with LEED at each temperature and no degeneration or reconstruction was found during the measurements.

It should be pointed out that in ARPES the incoming light warms the surface and there could be a few degrees difference between the temperature of the surface from which electrons are ejected and the temperature of the cold figure which we quote in the paper.

EDCs obtained by LRM are depicted in Fig. 5.
C. Neutron diffraction

The neutron diffraction experiments was carried out at Paul Scherrer Institute (SINQ, PSI). The crystal was mounted on an aluminium sample holder with the $\hat{c}$ perpendicular to the neutron beam; $(1, 0, 0) - (0, 1, 0)$ scattering plane. The collimation was 80'-40'-80'. Beryllium filter was placed before the analyzer to remove higher order neutrons. The instrument has a nine-blade pyrolytic graphite (PG) analyzers. The diffraction studies were performed with 4.04Å (5 meV) neutrons, using all blades to create a 2D color plot. The sample was aligned in such a manner that the area of interest (commensurate and incommensurate magnetism) was measured in the center blade. The incommensurate part was measured in a $(0, 1 + \delta q, 0)$ scan direction. The high temperature data was subtracted to remove the $\lambda/2$ contribution form the $(2, 0, 0)$ structural Bragg peak. For the commensurate part, the measurement was performed with a scan direction $(\delta q, 1 + \delta q, 0)$ to avoid the incommensurate contribution.

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