Stripe order of $La_{1.64}Eu_{0.2}Sr_{0.16}CuO_4$ in magnetic fields studied by resonant soft x-ray scattering

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Abstract

We present results on the magnetic field dependence of the stripe order in $La_{1.64}Eu_{0.2}Sr_{0.16}CuO_4$ (LESCO). Using resonant soft x-ray scattering at the oxygen K-edge to probe the (0.259,0,0.648) superlattice reflection, which is commonly associated to charge stripes, we found no pronounced difference in the wave vector, peak widths and integrated intensity for magnetic fields up to $B = 6$ T. This is in strong contrast to the behavior observed for $La_{1.875}Sr_{0.125}CuO_4$, where a stabilization of the charge modulation in high magnetic fields has been demonstrated.

The relation of spatial electronic ordering and superconductivity in the cuprate materials currently receives a lot of attention. A major reason for this large interest is given by the expectation that this relation may be key to better understand the complex electronic phase diagram of these materials, which in turn might pave the way to ultimately understand the high-temperature superconductivity itself.

Competing spatial electronic order and homogeneous d-wave superconductivity (dSC) has been well established in $La_{2-x}Ba_xCuO_4$ (LBCO) [1, 2] and LESCO [3] where a structural distortion in the low-temperature tetragonal (LTT) phase stabilizes the so-called stripe order. In this ordered phase, the holes doped to the CuO_2 planes are believed to condense into one-dimensional charge stripes that separate antiferromagnetically ordered regions. Just recently electronic order, associated with a charge density wave, was also reported to compete with dSC in other cuprate materials, such as $YBa_2Cu_3O_{7-x}$ [4–8], $HgBa_2CuO_{4+\delta}$ [9] and $(Bi_{2-x}Pb_x)(Sr_{2-y}La_y)Ca_{n-1}Cu_nO_{2n+4+\delta}$ [10–13]. In these cases, however, no long-range magnetic order has been detected, i.e., the localized spin moments appear to remain disordered down to low temperatures.

In cases where dSC competes with spatial electronic order, the application of a c-axis magnetic field usually stabilizes the electronic order at the expense of the competing dSC, as demonstrated for $YBa_2Cu_3O_{7-x}$ (YBCO) [14], LBCO [15] or LSCO [16]. Notwithstanding, there can also be a magnetic field effect on the stripe order itself, if there is no competing dSC state, since the stripe order involves antiferromagnetic spin order. An influence of external magnetic fields on the stripe order has indeed been reported for LSCO with x=0.145, where fields larger than 7 Tesla can promote AFM order and compensate for non-optimal doping [17]. Such an effect clearly goes beyond a simple competition between dSC and electronic order. A magnetic field dependence may even be possible for systems like YBCO and $(Bi_{2-x}Pb_x)(Sr_{2-y}La_y)Ca_{n-1}Cu_nO_{2n+4+\delta}$ for which the density wave shows no long-range magnetic order, but localized spins are still expected to exist. So far, experimental results can not rule out that there is an additional magnetic field dependence of electronic order that exists independently of a competing dSC. One candidate is given by the Zeeman energy of the spins in external fields, which not only depends on the field but also on the amount of ordered moments and might hence be limited to low temperatures in weak fields. Early neutron experiments on the SO of LSCO showed enhanced SO characterized by an onset of 3D charge order very similar to the observations in [18] but already in fields smaller 6

Tesla [16, 19]. Similar results have been reported for the stripe order in LBCO [20]. In all cases, it was found that the magnetic field can only influence the stripe order if the compound is superconducting. There are however a number of unresolved questions. The field effect seems to be almost always require a temperature of $T < T_c(H = 0)$, even though the actual critical temperature can be significantly lower in a magnetic field. This has been explained by proposing that locally, superconductivity starts always at $T_c(H = 0)$. Absence of field effects has been reported for stripe ordered systems without SC, but always in the vicinity of the stripe stabilizing $x = 1/8$ doping level. [17]. Although these studies generate a consistent picture in which SC is needed to mediate an influence of magnetic fields on charge order in moderate fields, one could argue that the inability of fields to manipulate stripe order at low temperatures without SC stems from the fact that stable stripes close to x=1/8 doping cannot be further enhanced since such stripes represent already represents the most stable CO state possible. Therefore, studying a stripe-ordered compound far away from stability but in the absence of SC serves as a final cross check. Furthermore, even in case the dominant mechanism of influencing CO by fields requires SC, such a study explores potential additional weaker field dependent effects independent of SC at low temperatures. LESCO is such a system, with doping dependent CO around x=1/8 stabilized by a structural distortion, which at the same time suppresses SC for a large range of doping levels. In contrast to LBCO, in LESCO T_{SO} and T_{CO} are well separated from T_{LTT}, which allows to study the influence of magnetic fields on stripes in the entire temperature range of CO without interfering structural or SC phase transitions. By choosing a Sr content that differs significantly from 1/8 (but is still close enough to deliver electronic order) we are able to determine if weakend charge stripes are susceptible to magnetic fields regardless of the presence of a superconducting phase.

We extend previous studies on stripe ordered cuprates and report resonant soft x-ray scattering (RSXS) [21] measurements on LESCO exposed to a magnetic field. LESCO undergoes a structural phase transition from an orthorhombic (LTO) to a tetragonal (LTT) phase at $T_{LTT} \approx 130\,\mathrm{K}$ and, while LSCO shows superconductivity with $T_c \approx 30\,\mathrm{K}$ [22], LESCO only becomes superconducting at $T_c \approx 5K$ for our Sr content [3]. This allows to investigate the effect of external magnetic fields on the stripe order in the absence of competing dSC.

Furthermore, even though the direct relation between spin order (SO) and the so-called charge order (CO) is known from the relation of their wave vectors $\delta_{SO} = 2\delta_{CO}$ [20, 22–24],

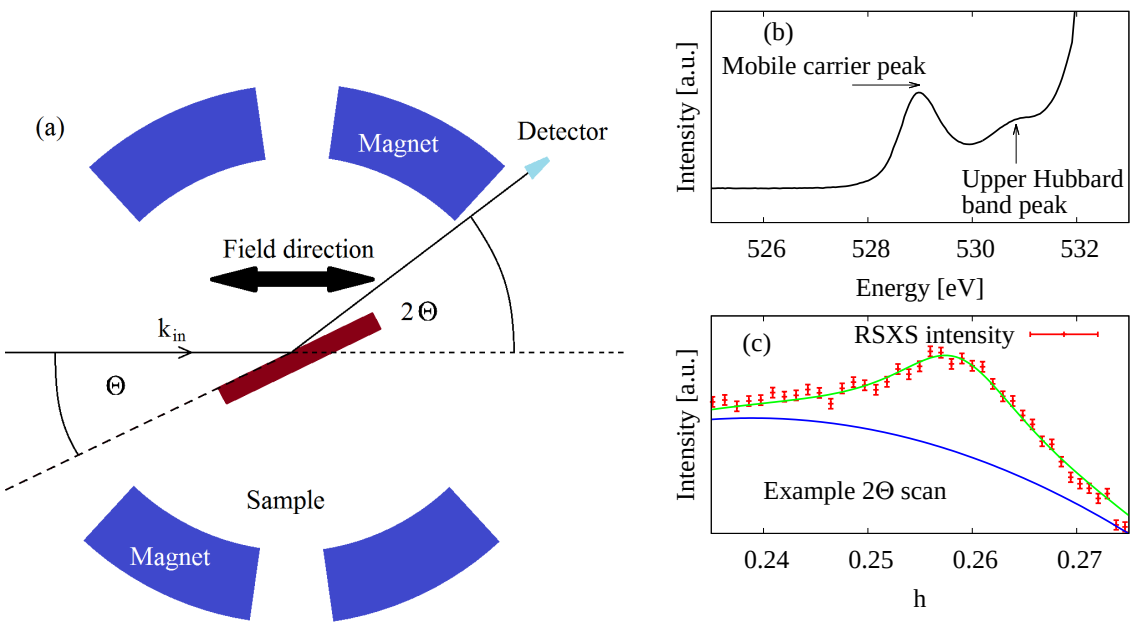

FIG. 1. (a) Experimental setup for RSXS and XAS experiments. (b) XAS total yield spectrum of LESCO near the O K absorption edge at $T = 52.5$ K. (c) Intensity of a 2Θ RSXS scan for $B = 0$ T, $T = 5$ K around the (h,0,l)=(0.259,0,0.648) superlattice reflection. On the x axis, the in-plane component h of the x-ray scattering vector is shown. The x-ray intensity is shown in red, the Lorentzian fit according to Eq. 1 is shown in green and the background is shown in blue.

there is no final conclusion on the role of SO in the temperature and field dependence of CO.

The LESCO sample used for this experiment was grown using the traveling solvent floating-zone method. The RSXS experiments were performed at the BESSY undulator beam line UE 46-PGM1 using a two-circle high-field diffractometer. The Sr content $x = 0.16$ was determined from the wave vector of the CO, the CO-transition temperature T_{CO} [23] and from the intensity of the upper Hubbard band peak of the x-ray absorption (XAS) spectra [25]. RSXS at the O K-edge is a direct approach to charge order, as the peak intensity is directly related to spatial modulations in the 2p valence states of oxygen. All RSXS scans have been performed at $\Theta = 27.5°$, so that the magnetic field along the sample c-axis was $B_c = 2.76$ T (cf. Fig. 2 a).

In Fig. 1 (b) we present XAS data for O K edge of the studied LESCO single crystal measured via the total electron yield. In accordance with previous studies [26, 27] we find absorption pre-peaks at 529.1 eV and 531 eV, which result from transitions into the O $2p$

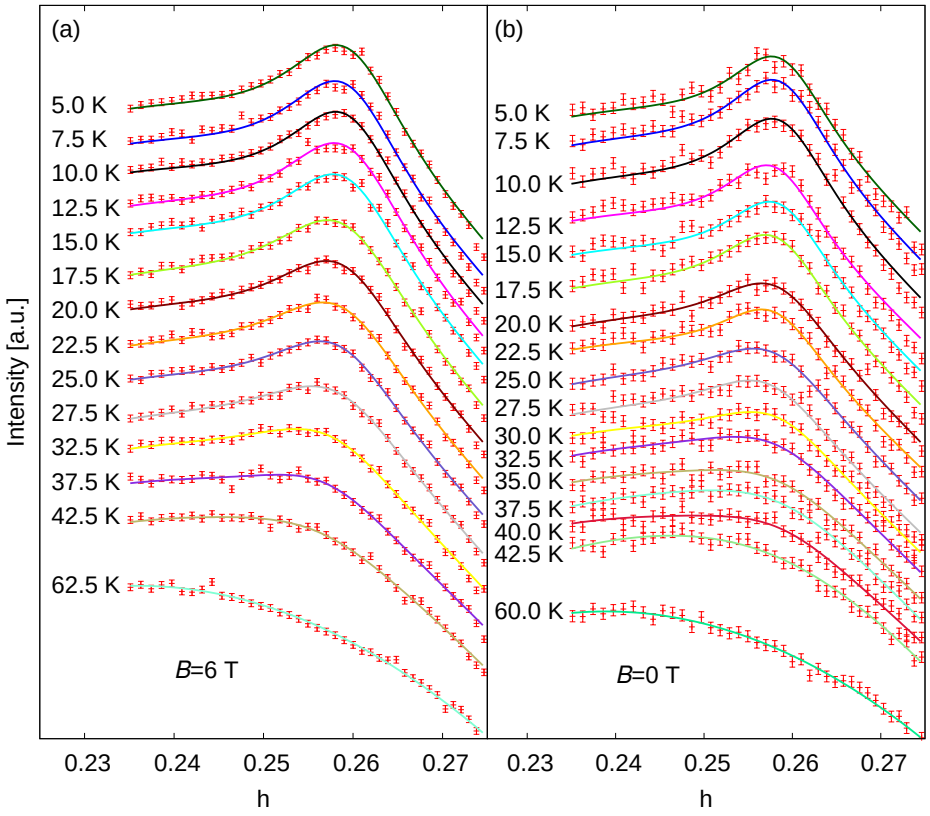

FIG. 2. RSXS (red bars) and Lorentzian fits on the electronic order peak for $B = 6$ T (a) and $B = 0$ T (b). For each scan, α, k, s and h_0 from Eq. (1) were free fit parameters. β and γ were assumed to depend on the magnetic field, but not on temperature and taken from the RSXS scans at $T = 60$ K. For $T > 42.5$ K, reliable fits of the RSXS could not be achieved due to the strong correlation of fit parameters. The data for 62.5 K (60 K) were thus fitted with k in Eq. 1 set to zero. For $B = 6$ T (a), the RSXS signal of three consecutive, identical scans was summed up to achieve superior statistics, while for $B = 0$ T, the RSXS was only measured once for each temperature.

doped hole states in the conduction band and into the upper Hubbard band, respectively. We denote the wave vector $\mathrm{Q} = 2\pi\,(h/a, k/b, l/c)$ with Miller indices (h, k, l) where in the LTT phase a = b = 3.79 Å and c = 13.14 Å.

A typical 2Θ-scan through the $(0.259, 0, 0.648)$ superlattice peak taken at T=5 K and a photon energy of $E = 529.1$ eV is shown in Fig. 1 (c). All peaks measured for different B

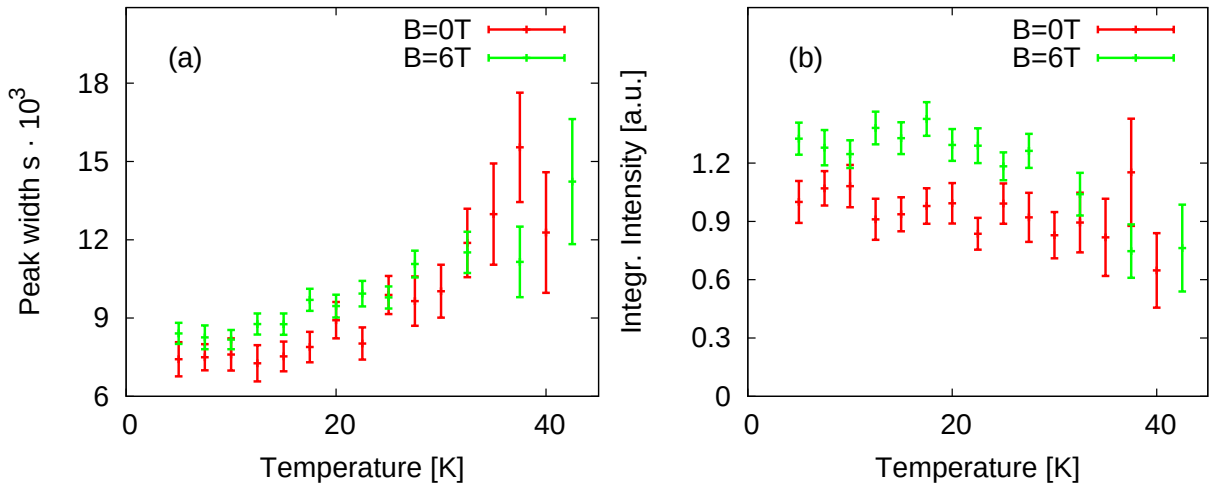

FIG. 3. (a) Peak width s from Lorentzian fits of the RSXS in Fig. 2. The electronic order peak is broader when a magnetic field is applied. The weak variation of the peak width with temperature is similar for both cases. (b) Integrated intensity of the electronic order peak at $B = 0$ T (red) and $B = 6$ T (green), taken from Lorentzian fits with Eq. 1. The electronic order peak is more intense in a magnetic field and the transition temperature T_{CO} is increased.

and T were fitted with a Lorentzian lineshape plus a quadratic background:

$$I(h) = \alpha + \beta(h - 0.26) + \gamma(h - 0.26)^2 + \frac{ks}{(s^2 + (h - h_0)^2)} \tag{1}$$

Here, α, β and γ parametrize the quadratic background. k, s and h_0 parametrize the height, width and position of the Lorentzian peak. β and γ were taken from fits at $T = 60$ K, where the electronic order has vanished and assumed to be independent of temperature. The fits to the RSXS data are shown in Fig. 2. We found that the peak width s increases weakly in the temperature region where the data allows for a reliable analysis. The intensities of the fitted superlattice peaks are shown as a function of magnetic field B and temperature in Fig. 3 (b). We find a decrease in intensity with increasing temperature and indications for a weak stabilization of the probed stripe order in magnetic fields. This is further illustrated in Fig. 4, where the fitted background has been subtracted from the RSXS to facilitate the comparison of the two data sets.

In conclusion we have presented measurements of temperature and magnetic field dependence of electronic order in $La_{1.64}Eu_{0.2}Sr_{0.16}CuO_4$. In contrast to materials, where the electronic order competes with dSC, we do not observe a pronounced effect of the magnetic

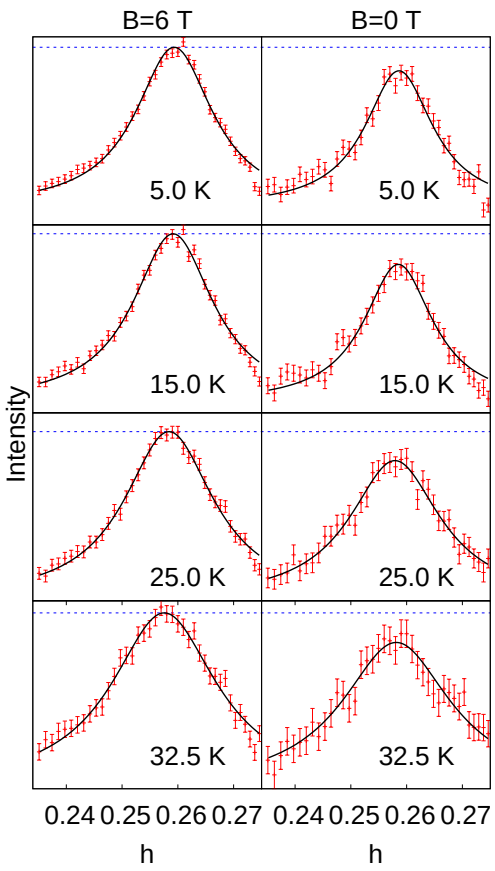

FIG. 4. Selected RSXS and Lorentzian fits on the electronic order peak for $B = 6$ T and $B = 0$ T. Only the Lorentzian contribution from Eq. (1) is shown, while the background was subtracted from fits and experimental data. For each scan, α, k, s and h_0 from Eq. (1) were free fit parameters. β and γ were assumed to depend on the magnetic field, but not on temperature and taken from the RSXS scans at $T = 60$ K. For $B = 6$ T, the RSXS signal of three consecutive, identical scans was summed up to achieve superior statistics, while for $B = 0$ T, the RSXS was only measured once for each temperature. Blue dotted lines are a guide to the eye for the $B = 6$ T maximum intensity. For all measured temperatures the superlattice peaks at 6 T are slightly more intense as compared to zero field.

field on the probed stripe order within the studied magnetic field range. Additional mechanisms independent of SC are at least one order of magnitude weaker. Nonetheless, for all measured temperatures the superlattice peaks at 6 T are slightly more intense as compared to zero field. This points towards a finite coupling of the electronic order in $La_{1.64}Eu_{0.2}Sr_{0.16}CuO_4$ to magnetic fields, which is not related to the suppression of

competing dSC. The possibility to manipulate stripes in the absence of SC could be an opportunity to disentangle the coupling between SO and CO by applying significantly stronger external fields.

Indeed, for YBCO a pronounced effect on the charge order has been found for magnetic fields well above 15 Tesla [18]. This, together with the present results, strongly motivates to also perform high-field RXD studies on the stripe order in LESCO. In any case, the magnetic field dependence observed by us is very weak, which further supports earlier conclusions that the stabilization of the electronic order in magnetic fields in, e.g., LBCO and YBCO is to be due to the suppression of competing dSC.

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