Evolution of magnetic stripes under uniaxial stress in $La_{1.885}Ba_{0.115}CuO_4$ studied by neutron scattering

Machteld E. Kamminga [1,*] Kristine M. L. Krighaar [1] Astrid T. Rømer [1] Lise Ø. Sandberg [1] Pascale P. Deen [1,2]
Martin Boehm [3] Genda D. Gu [4] John M. Tranquada [4] and Kim Lefmann [1,†]
[1]Nanoscience Center, Niels Bohr Institute, University of Copenhagen, 2100 Copenhagen Ø, Denmark
[2]European Spallation Source ERIC, Partikelgatan 224, 84 Lund, Sweden
[3]Institut Laue-Langevin, 71 Avenue des Martyrs, CS 20156, 38042 Grenoble Cedex 9, France
[4]Condensed Matter Physics and Materials Science Division, Brookhaven National Laboratory, Upton, New York 11973, USA

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We present the effect of uniaxial stress on the magnetic stripes in the cuprate system $La_{2-x}Ba_xCuO_4$ with $x = 0.115$, previously found to have a stress-induced enhancement in the superconducting transition temperature. By means of neutron scattering, we confirm that the static stripes are suppressed by stress, pointing towards a trade-off between superconductivity and static magnetism, in direct agreement with previously reported muon spin rotation measurements. Additionally, we show that some of the reduced weight in the elastic channel appears to have moved to the inelastic channel, while we can exclude the opening of a spin gap down to an energy of 1 meV. Moreover, a stress-induced momentum shift of the fluctuations towards the typical 1/8 value of commensurability is observed, while no change in periodicity is seen in the static stripe signal. These results impose a strong constraint on the theoretical interpretation of stress-enhanced superconductivity in cuprate systems.

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I. INTRODUCTION

The compound $La_{2-x}Ba_xCuO_4$ (LBCO) is famous for exhibiting pronounced spin-charge correlations known as stripes [1–4], which have been commonly observed in all hole-doped cuprate compounds [5–10]. At a doping value of $x = 1/8$, the stripes become especially pronounced and are often accompanied by a suppression in the superconducting critical temperature T_c. In LBCO this suppression is particularly strong: Three-dimensional superconductivity sets in at $T_c \simeq 4$ K at 1/8 doping, i.e., a much lower temperature than compounds with slightly smaller or larger dopings, which display $T_c \geqslant 30$ K. However, within this "1/8 phase," two-dimensional superconducting fluctuations are still found up to $T_{c,2D} = 40$ K, coinciding with the temperature at which static spin stripes are observed with neutron scattering [11,12]. This behavior can be understood in terms of a spatially modulated superconducting order, the pair-density wave (PDW), which is truly two dimensional and antagonistic to uniform d-wave superconductivity [5,13,14].

The tendency towards spin and charge stripe order and the intricate interplay of these types of correlations with superconductivity have motivated enormous scientific activity during the last three decades [4,6,15,16]. It is quite clear that the two phenomena compete to a large extent, most explicitly at the 1/8 anomaly. One key question is whether there exists a way to improve superconductivity by disrupting stripe order, for example, by introducing additional disorder or strain.

In this regard, it was recently demonstrated that disorder created by proton irradiation in LBCO gave an enhanced T_c [17]. In a different approach, presented by Guguchia and coworkers in Ref. [18], a moderate uniaxial stress was applied within the CuO_2 crystal plane and found to facilitate three-dimensional (3D) superconductivity at elevated temperatures in a LBCO crystal close to the 1/8 anomaly, namely for $x = 0.115$. A stress of only 25 MPa was sufficient to obtain a $T_{c,\text{onset}}$ of 32 K, compared to 10 K at ambient pressure, and at 37 MPa, the stress effect is almost completely saturated [18]. This is in great contrast to hydrostatic pressure experiments on LBCO, which show that a pressure of a couple of GPa is needed to have a significant impact on the structure and superconducting properties [19–21]. The effect of uniaxial stress on T_c in a LBCO-related stripe-ordered cuprate was first demonstrated by Takeshita *et al.* [22], showing that stress applied along the tetragonal [110] was about three times more efficient than along the tetragonal [100]. Notably, in the uniaxial stress study in Ref. [18], the magnetic volume fraction was determined by muon spin rotation (μSR) measurements and found to decrease with increasing stress, indicating that the volume fraction of the magnetic order anticorrelates with superconductivity.

*Present address: Condensed Matter and Interfaces, Debye Institute for Nanomaterials Science, Utrecht University, 3508 TA Utrecht, The Netherlands; m.e.kamminga@uu.nl
†lefmann@nbi.ku.dk

In this paper, we investigate the effect of uniaxial stress on LBCO $x = 0.115$, similar to the crystal investigated in Ref. [18], by elastic and inelastic neutron scattering. We confirm the decrease of static magnetism as stress is applied along the diagonal Cu-Cu crystal axis. Furthermore, we observe that the inelastic signal at an energy transfer of 1 meV increases slightly and displays an intriguing stress-induced shift towards commensurability, i.e., towards a periodicity of eight lattice spacings, while no similar effect is seen for the elastic signal.

II. EXPERIMENT

The sample is a 0.76-g single crystal of LBCO, $x = 0.115$ with $T_c \sim 12$ K, grown by the traveling-solvent floating-zone method [23]. The crystal was oriented with the $[1\bar{1}0]$ direction vertical and the [0.615 0.5 0] and [001] directions in the horizontal scattering plane. The crystal was subject to uniaxial stress along the tetragonal $[1\bar{1}0]$, i.e., along the diagonal Cu-Cu direction, using a home-built pressure cell with *in situ* pressure readout, optimized for neutron scattering. This state-of-the-art CuBe pressure cell is specifically designed for uniaxial stress neutron experiments up until 3 GPa, overcoming some of the greatest challenges currently present in such experiments: small sample sizes and nonuniform background signals. A drawing of the pressure cell, as well as additional information regarding the sample size, is given in the Supplemental Material (SM) [24]. A more elaborate description of the cell and its applications will be given elsewhere [25].

The main experiment took place on the cold neutron triple-axis spectrometer ThALES at Institut Laue-Langevin (ILL), Grenoble [26] with the pressure cell and sample cooled by a standard Orange cryostat. All the measurements were performed with a constant $E_f = 5$ meV and used a double focusing monochromator and a horizontally focusing analyzer. All scans in reciprocal space for the elastic and inelastic magnetic stripe signals were performed as pure sample rotation scans, in order to keep the background constant [27].

The inelastic signal was measured at the incommensurate stripe position at (0.615 0.5 2) at energy transfer $\Delta E = 1.0$ meV and 20 K, using no beam collimation. To measure the elastic signal at the (0.615 0.5 2) incommensurate position, $40'$ collimation was inserted before and after the sample to improve resolution and reduce the background at 2, 20, and 45 K. The stress was applied at ambient temperatures. After that, the elastic and then the inelastic scans were repeated. Due to time constraints, however, the background measurements at 45 K were not repeated, as we did not expect any change with stress. Finally, for normalization purposes, we measured the transverse acoustic phonon around the (110) position at 2.0 meV and 90 K. More experimental details are given in the SM [24].

III. RESULTS AND DISCUSSION

After applying a uniaxial stress of 30 MPa along the tetragonal $[1\bar{1}0]$ direction on our $La_{1.885}Ba_{0.115}CuO_4$ crystal, the lattice parameters changed significantly and an orthorhombic strain was induced in the sample: The d spacing of the (110) plane, measured in plane, increased from 5.3309(8) to 5.3460(3) Å, a relative change of around 0.3%. Furthermore, the other in-plane-oriented lattice parameter c changed from 13.2764(6) to 13.1287(6) Å under applied stress.

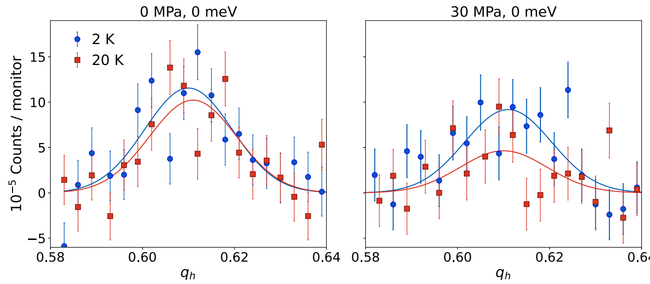

FIG. 1. Background-subtracted elastic signals at 0 MPa (left) and 30 MPa (right), each comparing 2 K and 20 K data.

In Fig. 1 we compare the elastic stripe peak at (0.615 0.5 2) with and without stress, measured at 2 and 20 K. Note that 2 K is below T_c, while 20 K is above at 0 MPa, but below T_c at 30 MPa [18]. Fitting parameters and raw data without background subtraction are given in the SM [24]. The peak width of the elastic signals was determined by fitting the combined 2 and 20 K data without stress (see Fig. S2 in the SM [24]). As shown in Fig. 1, no significant change in peak position is observed, within an uncertainty of 0.003 r.l.u. Muon experiments cannot give this type of structural information [18].

In our data, a significant suppression of the static magnetic signal is visible with applied temperature for the 30 MPa data, while the effect is below the error bar for the data at ambient pressure. These results indicate a direct trade-off between the static spin-stripe order signal intensity and 3D superconductivity. Note that this is in agreement with our expectations, since charge stripes are good for pairing, but spin-stripe fluctuations get in the way of establishing phase coherence between neighboring stripes. Moreover, spin-stripe order induces PDW superconductivity, which is primarily two dimensional due to a frustrated interlayer Josephson coupling [1,14].

The temperature-dependent suppression of the elastic spin-stripe peak by stress is in strong agreement with the μSR data presented by Guguchia *et al.* [18]. Note that neutron scattering is a volume-integrating probe in reciprocal space, and the measured intensity entails both the magnetic moment and its volume fraction, while μSR measurements allow for independent measurements of both variables. However, Guguchia *et al.* find that the magnetic moment in LBCO stays unaffected by stress within 30 MPa [18]. Therefore, we directly compare our scattered neutron intensity to the magnetic volume fractions obtained by μSR [28], as shown in Fig. 2. Despite using different crystals, but with the same doping level, and probing the magnetism at different timescales, the results of the two independent techniques clearly show the same trend. Note that in our study, we applied the stress at an angle of 3° from the tetragonal $[1\bar{1}0]$ direction, while Guguchia *et al.* applied their stress at an angle of 15° from this direction [18], which would correspond to a slightly lower value of applied stress when using our geometry. Note that in Fig. 2 we have implicitly assumed that the experimental conditions are unchanged during application of pressure. In principle, the

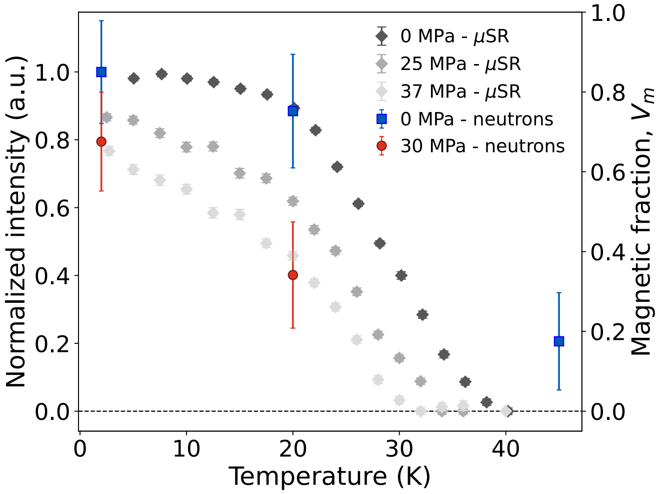

FIG. 2. Comparison of elastic stripe peak intensities with the magnetic volume fraction obtained by μSR, as a function of temperature and stress. The 2 K, 0 MPa data point is normalized to a magnetic volume fraction of 85%, matching the 0 MPa μSR data, and the other data points are scaled accordingly. μSR data reproduced with permission from Guguchia *et al.* [18].

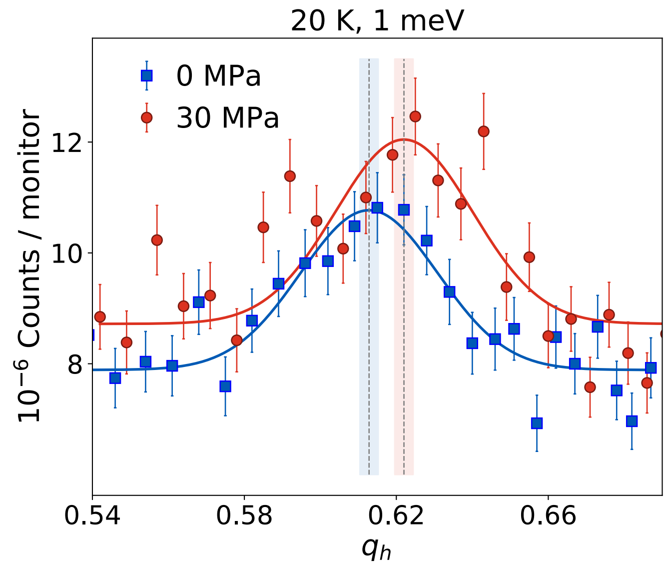

FIG. 3. Inelastic signals ($\Delta E = 1.0$ meV) at 20 K without applied stress (blue) and with 30 MPa (red). The vertical dashed blue and red lines display the fitted peak positions with the error bar from the fit (1σ).

illuminated sample volume could have changed slightly in the process, causing an unknown scaling between our two data sets. However, the temperature effect of the stripe intensity is a robust feature of our data, and we can confidently state that this effect is pressure dependent, confirming the observations by Guguchia *et al.* Note also that a small elastic intensity was found at 45 K at 0 MPa, with the error bars nearly reaching zero (see Fig. S4 in the SM [24]). We argue that this residual intensity could be caused by integrating over the instrumental resolution of 0.2 meV, which therefore incorporates a small fraction of the dynamic stripes that extend well beyond T_c [12].

In Fig. 3 we show the inelastic stripe peak at (0.615, 0.5, 2) with and without stress, measured at 20 K with an energy transfer of $\Delta E = 1.0$ meV, and fitted with a constant background. Fitting parameters are given in the SM [24]. The presence of a highly significant (10σ) peak at 30 MPa rules out the possibility of a stress-induced spatially uniform spin gap of $\Delta E = 1.0$ meV or higher. Note that LBCO outside the 1/8 anomaly, i.e., at $x = 0.095$, also does not display a gap [29,30], but our results indicate that the stress-enhanced restoration of the superconductivity to the non-1/8 level does not imply the opening of a spin gap. Furthermore, in critically doped $La_{2-x}Sr_xCuO_4$, i.e., the Sr analog of LBCO, the absence of a spin gap at the 1/8 anomaly is quite robust. The elastic stripe signal is easily increased by a magnetic field, but the dynamic stripe signal is hardly affected, indicating a disconnect between the elastic and dynamic stripes in critically doped cuprates [31].

In our work, the dynamic stripe intensity at 20 K is not suppressed by stress, in contrast to the elastic signal. In fact, there is a hint of an enhancement of the peak intensity by stress, although the enhancement is not statistically significant with our level of uncertainty. Note that large changes in intensity due to the total intensity sum rule would not be expected, since the loss of spectral weight in the elastic channel is quite small and is likely distributed over a larger energy range. These observations put a relevant constraint on the interpretations of what happens in the stress-induced T_c-enhanced regime.

More strikingly, an unexpected shift is observed in the inelastic peak position with stress: A change in q_h from 0.613(2) to 0.622(2) is found. This shift is significant at a 99.7% level, as the difference between the two peak values is more than 3σ away from zero. Including the possibility for a change in background slope with pressure does not change this conclusion, as discussed in relation to Table S4 in the SM [24].

To understand this change in peak position, it may be relevant to take account of the evidence for significant spatial variations in local hole concentration provided by nuclear magnetic resonance studies on $La_{2-x}Sr_xCuO_4$ [32,33]. We know that the average stripe wave vector varies with the average hole concentration (at least for $x < 1/8$) [3], and it is reasonable to expect that this correlation will also occur on the local scale. Could the dynamic character depend on the local hole content and stripe wave vector? Such a hypothesis provides a natural interpretation for the previously observed behavior in LBCO $x = 0.095$ [29] and in oxygen-doped La_2CuO_{4+y} [34], where the elastic spin-order peak is at an incommensurability closer to 1/8 while the low-energy spin excitations are centered at a smaller incommensurability. If regions with a local hole concentration far from 1/8 tend to have a purely inelastic signal, while those close to 1/8 have spin-stripe order, then the former regions may be sufficient to establish three-dimensional superconducting order at a significant T_c. In the cases of LBCO $x = 0.095$ [29] and La_xCuO_{4+y} [34], the superconducting transitions are at 32 and 40 K, respectively, despite the absence of a net spin gap. In the present case of LBCO $x = 0.115$, the uniaxial stress reduces the rotational anisotropy of the average structure within the CuO_2 planes, thus lowering the potential for charge-stripe ordering, with the impact likely depending on the local hole density. An inhomogeneous depression of spin-stripe order may be sufficient to yield a sharp rise in a measure of the bulk T_c [18]. Future work is required to gain insight into stress effects on phase inhomogeneity.

IV. CONCLUSIONS

In conclusion, we have shown how the magnetic stripes in $La_{1.885}Ba_{0.115}CuO_4$ evolve under uniaxial stress along the tetragonal $[1\bar{1}0]$ direction using neutron scattering. Our results show that the elastic stripes at 30 MPa stress are suppressed more strongly by temperature, directly matching the reduced magnetic volume fraction in the T_c-enhanced regime found by muon experiments [18]. Furthermore, we show that stress does not open a spin gap at 1 meV and that the reduced weight in the elastic channel appears to have moved to the inelastic channel. Moreover, we observe a notable shift in the inelastic peak position towards the typical value of 1/8, while a similar effect is not seen in the elastic signal. Our results provide a significant constraint on the theoretical interpretation of stress-induced enhancement of T_c in LBCO, that will be of relevance to other cuprate systems as well. They support the picture of a subtle competition between spin-stripe fluctuations and superconducting phase order.

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