Effect of a magnetic field on the spin- and charge-density-wave order in $La_{1.45}Nd_{0.4}Sr_{0.15}CuO_4$

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The spin-density wave (SDW) and charge-density wave (CDW) order in superconducting $La_{1.45}Nd_{0.4}Sr_{0.15}CuO_4$ were studied under an applied magnetic field, using neutron and x-ray diffraction techniques. In zero field, incommensurate (IC) SDW order appears below ~ 40 K, which is characterized by neutron diffraction peaks at $(1/2\pm 0.134,1/2\pm 0.134,0)$. The intensity of these IC peaks increases rapidly below $T_{Nd}\sim 8$ K due to an ordering of the Nd^{3+} spins. The application of a 1 T magnetic field parallel to the *c* axis markedly diminishes the intensity below T_{Nd}, while only a slight decrease in intensity is observed at higher temperatures for fields up to 7 T. Our interpretation is that the *c*-axis field suppresses the parasitic Nd^{3+} spin order at the incommensurate wave vector without disturbing the stripe order of Cu^{2+} spins. Consistent with this picture, the CDW order, which appears below 60 K, shows no change for magnetic fields up to 4 T. These results stand in contrast to the significant field-induced enhancement of the SDW order observed in superconducting $La_{2-x}Sr_xCuO_4$ with $x\sim 0.12$ and stage-4 La_2CuO_{4+y}. The differences can be understood in terms of the relative volume fraction exhibiting stripe order in zero field, and the collective results are consistent with the idea that suppression of superconductivity by vortices nucleates local patches of stripe order.

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I. INTRODUCTION

Incommensurate (IC) magnetic correlations are one of the fascinating characteristics of the hole-doped high-T_c superconducting material $La_{2-x}Sr_xCuO_4$ (LSCO) and related compounds.[1] Dynamic IC correlations in superconducting LSCO have been observed using neutron scattering techniques near the optimal doping concentration $x=0.15$.[2–4] It was later established that the optimized superconducting transition temperature is inversely proportional to the IC spatial modulation period at a given Sr (hole) concentration x,[5] suggesting that the superconductivity and incommensurability are closely related with each other. On the other hand, *static* IC spin correlations have been extensively studied in $La_{2-x-y}Nd_ySr_xCuO_4$ (LNSCO). This was initially because of interest in the so-called 1/8 anomaly, which refers to the suppression of superconductivity in $La_{2-x}Ba_xCuO_4$ (LBCO) at $x=1/8$, that is accompanied by the appearance of the low-temperature tetragonal (LTT) $P4_2/ncm$ structure.[6]

Nd-doping in LSCO stabilizes the LTT structure over a wide range of x, and significantly suppresses T_c. During neutron scattering experiments on LNSCO with $0.08\leqslant x\leqslant 0.20$ and $y=0.4$, Tranquada *et al.*[7–10] observed elastic magnetic peaks at tetragonal positions $(1/2\pm\epsilon,1/2\pm\epsilon,0)$ that are almost identical to those of the inelastic IC peaks found in superconducting LSCO. They explained this static feature in terms of a two-dimensional (2D) stripe model in which hole-free antiferromagnetic (AF) regions are separated by one-dimensional stripes of hole-rich regions. Thus, their model places both spin-density-wave (SDW) and charge-density-wave (CDW) orders on the CuO_2 planes. Since the charge stripes become the antiphase boundaries of the AF regions, the magnetic modulation period is twice that of the charge density modulation. In fact, additional satellite peaks were observed by both neutron[8,10] and x-ray[11,12] diffraction techniques in LNSCO around the nuclear Bragg peaks at $(2\pm 2\epsilon,0,l)$ due to the charge density modulation, consistent with the stripe model as well as with more general coupled SDW and CDW models. Following these experiments, the same type of SDW order has been observed by neutron scattering in LSCO samples with $x=0.12$ (Refs. 13 and 14) and in oxygen-doped stage-4 $La_2CuO_{4+\delta}$ [LCO(δ)].[15] Surprisingly, no charge order peaks have been detected yet in these materials. In all of the above cases, the between-plane correlation length of the SDW order is of order or less than one lattice constant.

Since the stripe structure contains magnetic order, the effect of an external magnetic field on the stripe should provide important information about its nature. To date, a few neutron scattering experiments have been carried out under magnetic field to investigate the effects on the SDW order in LSCO with $x=0.12$ (Ref. 16) and $x=0.10$,[17] and in stage-4 LCO(δ).[18,19] All of these measurements show qualitatively consistent behavior, with the SDW peaks being substantially enhanced by applying a field perpendicular to the CuO_2 planes. Possible explanations of the enhancement of the

SDW peaks have involved suppression of spin fluctuations or competing superconducting and AF order[20–25] whose physical origin is the suppressed superconductivity together with the enhanced AF order in the vortex cores. However, the effects of a magnetic field on the stripe order itself remain unclarified.

In the present experiment, we have studied the effect of an applied magnetic field on the stripe order in superconducting $La_{1.45}Nd_{0.4}Sr_{0.15}CuO_4$. The stripe order at this particular composition has previously been characterized by neutron[9] and x-ray[12] diffraction and by the zero-field muon-spin-relaxation (μSR) technique,[26] and the superconductivity has been characterized by high-field magnetization measurements[27] and by transverse-field μSR.[26] We find that while an applied magnetic field of <1 T is sufficient to suppress the parasitic ordering of Nd^{3+} moments at the SDW wave vector, it has essentially no impact on the stripe order associated with the doped holes and copper spins.

The rest of the paper is organized as follows. After describing the experimental details in the following section, the neutron and x-ray scattering results are presented in Sec. III. These results are discussed in Sec. IV. There we first explain the response of the Nd moments in the magnetic field. Then we consider the lack of effect on the charge and Cu-spin stripes in the present sample, together with the field-induced response in LSCO and LCO(δ). Collectively, these results can be understood in terms of the ideas (1) that there is little coupling of a uniform magnetic field to the locally antiferromagnetic correlations of the stripe phase and (2) that the suppression of superconductivity in magnetic vortex cores results in the nucleation of patches of stripe order.

II. EXPERIMENTAL DETAILS

The single crystal of LNSCO ($x=0.15$ and $y=0.4$) used in this study is the same one used in Ref. 9. The sample was grown using the traveling-solvent floating-zone method and is 5 mm in diameter and 20 mm in length. The sample exhibits a structural transition from a low-temperature orthorhombic structure to a LTT structure at $\sim$80 K; the lattice constants at 5 K are $a=b=3.80$ Å and $c=13.1$ Å, corresponding to reciprocal lattice units of $a^*=b^*=1.65$ Å^{-1} and $c^*=0.48$ Å^{-1}.

The superconducting transition has been characterized on pieces of crystal grown in the same fashion as the neutron sample. From previously reported measurements of the magnetic susceptibility[9] and the thermodynamic critical field,[27] the transition temperature is approximately 10 K. To characterize the effect of a magnetic field applied along the c axis on the transition, the resistivity was measured, as shown in Fig. 1. As is frequently observed, the zero-field resistivity measurement indicates a higher transition temperature than does the susceptibility. We note the relatively large difference between T_c values of the susceptibility and resistivity measurements in this system compared to the LSCO and LCO(d) systems. Since the superconductivity in LNSCO is strongly suppressed by the CuO_6 octahedral tilt of the LTT structure, which pins the stripes, the local T_c is very sensitive to the local fluctuation in Sr and/or Nd concentration that cause the local fluctuation of the octahedral tilts. Bulk resistivity shows higher T_c if there are small patches with higher T_c that percolate through the sample. On the other hand, if they have a small volume fraction, the magnetization will not be affected. Thus, the relatively large difference of T_c values may be a characteristic feature in LNSCO. However, this effect has no impact on the conclusions that we will reach based on the neutron and x-ray measurements.

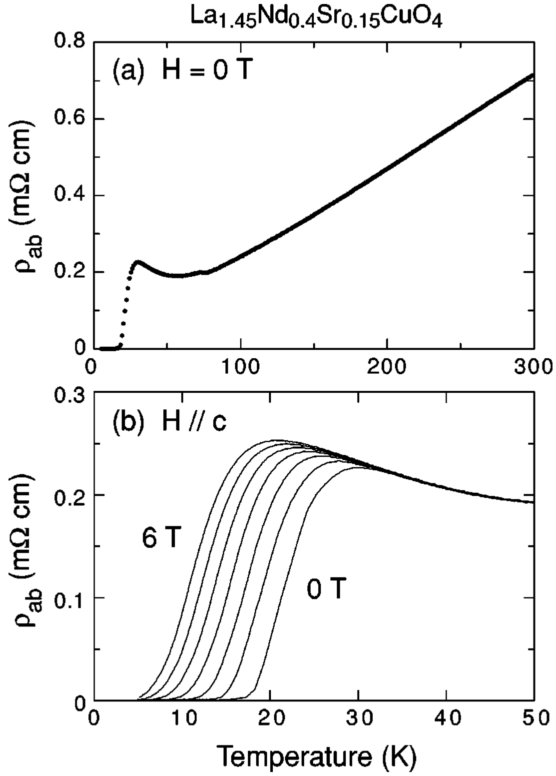

FIG. 1. (a) Temperature dependence of the in-plane resistivity. (b) Effect of a c-axis magnetic field on the in-plane resistivity. Data are shown for 0, 1, 2, 3, 4, 5, and 6 T.

The neutron scattering experiments were performed using the triple axis spectrometer SPINS installed on the cold neutron guide NG5 located at the NIST Center for Neutron Research. Highly oriented pyrolytic graphite crystals were used as monochromator and analyzer. An incident neutron energy of 5 meV with a horizontal collimation sequence 32′-80′-S-80′-open (S: sample) was utilized. Higher-order neutrons were removed from the beam by a cold Be filter located after the sample. The crystal was fixed to an Al holder by Gd cement and Al wire, and mounted in a cryostat equipped with a superconducting magnet. The a and b crystallographic axes were oriented in the horizontal plane to allow access to $(h,k,0)$ type reflections. With this configuration, the magnetic field was aligned perpendicular to the CuO_2 planes. During the experiments, we verified that the nuclear Bragg intensities did not change with field, thereby confirming that the sample was properly mounted, that is, the sample position was field independent.

The x-ray scattering experiments were carried out at the BW5 beam line at HASYLAB in Hamburg, Germany. The incident photon energy of 100 keV was selected by a

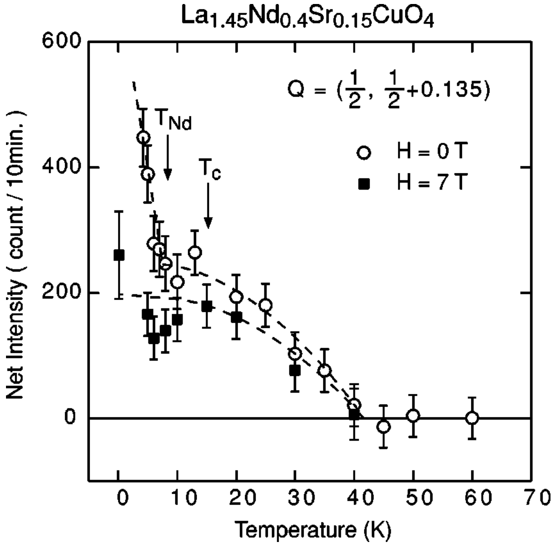

FIG. 2. Temperature dependence of the net IC peak intensity at $Q=(1/2,1/2+0.135)$ in zero field (circles) and 7 T (squares). Dashed lines are guides to the eye. The data in a magnetic field were measured on warming after field cooling from 60 K. In zero field, the intensity first appears below $\sim$40 K and grows rapidly below $T_{\rm Nd}\sim 8$ K due to the Nd^{3+} ordering. The rapid increase below $T_{\rm Nd}$ is suppressed at 7 T, but otherwise the intensity appears to be constant within the errors. This implies that the magnetic field destroys the Nd^{3+} ordering. Above T_c (or $T_{\rm Nd}$), there is at best a small diminution in intensity with magnetic field.

$Si_{1-x}Ge_x$ gradient crystal monochromator and analyzed by the same type of crystal. The sample was mounted in a superconducting magnet with the c-axis oriented perpendicular to the scattering plane and the field aligned perpendicular to the CuO_2 planes. The momentum resolution full width at half maximum measured at the (2,0,0) Bragg position was 0.015 Å^{-1} along [100] and 0.0014 Å^{-1} along [010].

III. NEUTRON AND X-RAY CROSS-SECTIONS

A. SDW order

In zero magnetic field, SDW IC peaks are observed at $(1/2\pm\epsilon,1/2\pm\epsilon,0)$, where $\epsilon=0.134$. The temperature dependence of the SDW peak intensity is plotted in Fig. 2 using open circles. The peaks first appear at 40 K, which agrees with the results of Ref. 9. The peak intensity increases rapidly with deceasing temperature below 8 K; this is due to the ordering of the Nd^{3+} spins.[8] Hereafter, we refer to this Nd ordering temperature as $T_{\rm Nd}=8$ K. On the other hand, the temperature dependence under magnetic field below $T_{\rm Nd}$ is significantly different. The squares in Fig. 2 represent the peak intensities measured under a 7-T magnetic field. Although there seems to be a small reduction of intensity, the temperature dependence above $T_{\rm Nd}$ is quite similar to that in zero field. Importantly, however, there is no longer a rapid increase in intensity below $T_{\rm Nd}$ at 7 T. These features are more clearly shown in Fig. 3, which shows peak profiles measured along $(1/2,1/2+q,0)$ at 4.3 K and 20 K. At 4.3 K (below $T_{\rm Nd}$), the peak intensity at 7 T is reduced to half of that in zero field, while there is no significant change with field in the peak profile at 20 K (above $T_{\rm Nd}$). For all profiles, the peak widths are slightly larger than the instrumental resolution width, which is represented by the thick horizontal bars. The solid lines in Fig. 3 are the results of fits to a resolution-convoluted 2D Lorentzian function of q. These fits show that the correlation length of the SDW order is $\sim$200 Å for all profiles, that is, only the intensity changes with temperature and magnetic field.

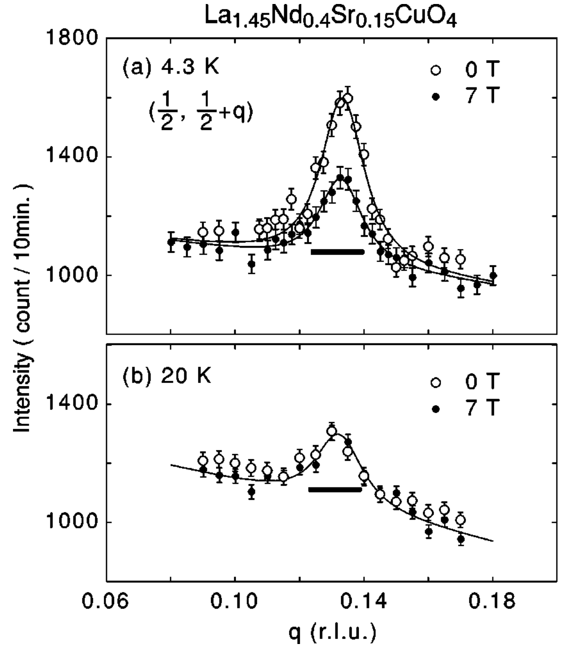

FIG. 3. Lineshape of the $(1/2,1/2+\epsilon,0)$ IC peak at (a) 4.3 K and (b) 20 K in zero field (open circles) and 7 T (closed circles). (Only the open circle is shown when the symbols overlap.) The data in the 7-T magnetic field were taken after field cooling from 60 K. Horizontal bars indicate the instrumental resolution. Solid lines are the results of fits to a two-dimensional Lorentzian function convoluted with the instrumental resolution. A clear reduction of the IC peak intensity is observed at 4.3 K (below $T_{\rm Nd}$), while no significant change occurs at 20 K (above $T_{\rm Nd}$).

The intensity of the SDW peak in zero field increases by more than an order of magnitude below $T_{\rm Nd}$, as indicated in Fig. 2. We find that the field-induced suppression of the SDW peaks is especially significant at the lowest temperatures. Figure 4(a) shows the field dependence of the SDW peak measured at $(1/2,1/2-\epsilon,0)$ at 0.1 K. In contrast to the factor of 2 reduction caused by 7 T at 4.3 K, the peak intensity is almost completely suppressed by a field of less than 1 T. The solid lines are the results of fits to a resolution-convoluted 2D Lorentzian squared function of q. The peak width is almost resolution limited and does not change with field. The field dependence of the peak intensity is shown in Fig. 4(b). The intensity decreases rapidly with increasing field and almost reaches the background at $H=0.7$ T. Although the intensity appears to be completely suppressed at $H\geqslant 0.7$ T, there is still a small remaining signal that is comparable to that observed just above $T_{\rm Nd}$. This intensity is shown in Fig. 2 by the solid square at the lowest temperature.

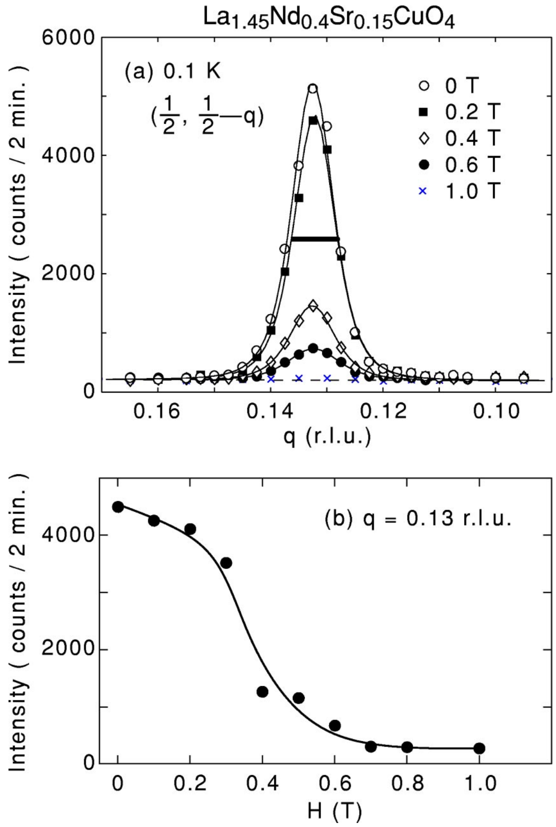

FIG. 4. (a) IC peak profiles at 0.1 K in different magnetic fields. The horizontal bar indicates the instrumental resolution. The solid lines are the results of fits to a two-dimensional Lorentzian-squared function convoluted with the instrumental resolution. (b) Field dependence of the IC peak intensity at 0.1 K. The solid line is a guide to the eye. Most of the intensity is suppressed by a magnetic field of 0.7 T. However, even at 7 T a weak intensity comparable to that observed above 8 K remains as shown in Fig. 2.

B. CDW order

The temperature dependence shown in Fig. 2 naturally suggests that the applied field primarily suppresses the Nd spin contribution to the SDW peaks. In particular, the temperature dependence at 7 T above T_{Nd} is very close to that in zero field, and the drastic increase of the SDW peak intensity below T_{Nd} disappears at 7 T. The next question is then how does the field affect the CDW peaks? To study this, we performed x-ray scattering experiments in an applied magnetic field. Figure 5 shows the temperature dependence of the CDW peak intensity measured at $(1.74,0,-0.5)$. Circles and diamonds correspond to data taken in zero field and 4 T, respectively. The choice of $L=-0.5$ was made because the structure factor has a maximum at that position.[11] The onset temperature is $\sim$60 K, which is consistent with the previous measurement for $x=0.15$ in Ref. 11, and is same as that reported for the $x=0.12$ sample.[8,11] As shown in Fig. 5, the temperature dependences with and without field are completely identical. The inset shows the field dependence of the intensity at 1.9 K and 4 K. We find, therefore, that while the SDW peak is strongly suppressed by application of a magnetic field below T_{Nd}, the CDW peak intensity is independent of field.

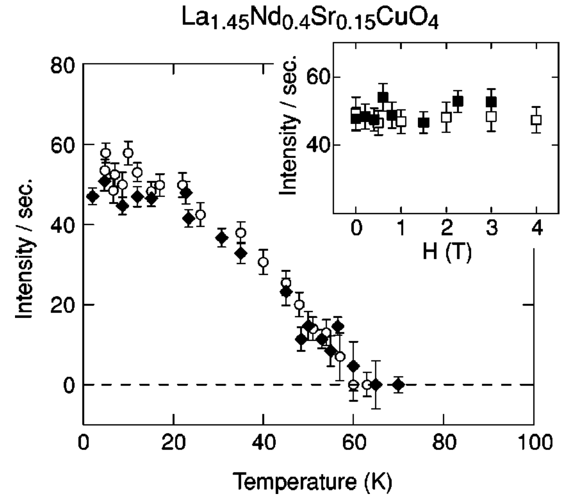

FIG. 5. Temperature dependence of the CDW peak intensity measured at $(1.74,0,-0.5)$ in zero field (circles) and in 4 T (diamonds). The inset shows the field dependence of the peak intensity at 1.9 K (open squares) and 4 K (closed squares).

IV. DISCUSSION

A. Nd response

From these results, it appears that the magnetic field perpendicular to the CuO_2 planes inhibits the Nd^{3+} spin ordering, but has at most a weak effect on the stripe structure itself. This picture confirms that the Nd spins simply follow the stripe order of the Cu spins and not the other way around. It also suggests that the correlation between Cu and Nd spins is weak as observed previously in the related material Nd_2CuO_4.[28] Below we discuss the Nd response in more detail.

The Nd spin contribution to the SDW peak intensity is dominant at the lowest temperatures;[8] therefore, the field dependence in Fig. 4(b) should relate to the magnetic response of the Nd ions. The magnetic fluctuations of the Nd ions in $La_{2-x-y}Nd_ySr_xCuO_4$ have been studied with neutron scattering by Roepke *et al.*[29] For a sample with $y=0.3$ and $x=0$ measured at low temperature, they resolved an excitation at 0.25 meV, which they attributed to a splitting of the Kramers-doublet ground state of Nd^{3+} by an exchange interaction with ordered Cu moments. In a sample with $y=0.6$ and $x=0.15$, the magnetic fluctuations appeared as quasielastic scattering with a half-width of $\Gamma/2=0.1$ meV. If we take this energy width to represent the effective exchange interaction appropriate for our sample $(y=0.4)$, then the external field that is required to give an equal Zeeman energy is $H_0=\Gamma/2m_{Nd}$, where m_{Nd} is the magnetic moment of a Nd ion. From the magnetization measurements of Ostenson *et al.*[27] on a crystal identical to ours, m_{Nd} is $3.2\mu_B$, which finally gives $H_0=0.54$ T. This estimate is in good agreement with the field at which the peak intensity drops, as shown in Fig. 4. We conclude that a modest uniform magnetic field is sufficient to align the Nd moments uniformly, thus removing their contribution from the SDW superlattice peaks.

The dominant part of the Nd contribution to the SDW peaks appears below T_{Nd}; however, there may also be a small contribution from Nd moments at higher temperatures.[8] The small decrease of the SDW peak intensity caused by the 7 T field for $T > T_{\mathrm{Nd}}$ (see Fig. 2) is likely due to the elimination of the Nd component. Note that the CDW intensity shows no significant change for applied fields up to 4 T.

B. Magnetic field, superconductivity, and stripes

In a recent μSR study[30] on LSCO with $x = 0.12$ and stage-4 LCO(δ), it was found that local magnetic (SDW) order occurred in only a fraction of the volume, 20% and 40%, respectively. Within that volume fraction, the average local hyperfine field is the same as in a uniformly stripe-ordered sample, $La_{1.48}Nd_{0.4}Sr_{0.12}CuO_4$.[26] Based on neutron diffraction studies,[17,14] the volume fraction exhibiting SDW order in LSCO with $x = 0.10$ should be much smaller. LSCO (Refs. 16 and 17) and LCO(δ) (Ref. 18) show a clear enhancement of the SDW peaks in the presence of a field applied perpendicular to the CuO_2 planes. This enhancement could result from a coupling of the magnetic field to the SDW order parameter, or from growth of the SDW volume fraction by suppression of the superconductivity.

A direct coupling to the SDW order has recently been observed in LSCO with $x = 0.024$ by Matsuda *et al.*[31] This sample is insulating at low temperatures and exhibits diagonal IC SDW order. A small reduction of the SDW peak intensity was found in an applied magnetic field. The effect was explained in terms of the reorientation of spins in half of the CuO_2 layers in order to align the canted spin components that result from the Dzyaloshinskii-Moriya exchange interaction. In the case of the parallel (vertical) stripes present in the superconducting phase, we would expect the orientation of the canted spin components to alternate in neighboring magnetic domains so that there would be no net coupling to a uniform field. The long correlation length observed in LNSCO vitiates the mechanism of Matsuda *et al.*[31] Furthermore, such a mechanism would not explain the field-induced *enhancement* in LSCO and LCO(δ).

The present results indicate that there is no significant direct coupling between a uniform magnetic field and the stripe order. This is consistent with expectations, given that the magnetic order is locally antiferromagnetic. It follows then that the field-induced growth of SDW order in LSCO and LCO(δ) must be due to suppression of the superconductivity. The superconductivity may coexist with SDW order in the regions of these samples, but the μSR results indicate that there must be a significant volume fraction where there is superconductivity without SDW order. It is presumably in these latter regions that new SDW order is generated by the applied field.[19] It is then understandable that the largest SDW growth with field occurs in LSCO with $x = 0.10$,[17] where the zero-field SDW volume fraction is quite small. It is also reasonable that there is no significant enhancement in the present crystal, which is reported to be uniformly SDW ordered by μSR.[26]

The applied field penetrates the sample in quantized vortices, with the superconducting order parameter going to zero within each vortex core. The possibility that Néel order might appear in the vortex cores was considered by Arovas *et al.*[20] A more relevant model, in which SDW and superconducting order can coexist, was analyzed by Demler *et al.*,[21,22] with some refinements proposed later by Kivelson *et al.*[23] (see also Refs. 24 and 25). In this model, the SDW order can be induced in a region extending beyond the vortex core, similar to the "halo" effect observed by scanning tunneling microscopy[32] on $Bi_2Sr_2CaCu_2O_{8+\delta}$. The long magnetic correlation lengths observed at high field in LSCO (Refs. 16 and 17) and LCO(δ) (Ref. 18) indicate that the halo radius may be >100 Å. It seems likely that weak Ising anisotropy, which is known to be present at low doping,[31] is important for establishing static order in domains of finite extent. Based on the present results, we would expect the SDW order to saturate when the vortex spacing is comparable to the halo diameter.

Finally, continuing with the same argument, the lack of a significant change in the stripe order in our LNSCO sample provides further confirmation that the stripe order is uniform in the sample consistent with the μSR measurement.[26] If it were not, then there should be regions with superconductivity and no SDW order, and we would expect to see an increase in the SDW order as vortices are induced in those regions. This result also confirms that the bulk superconductivity[26,27] must coexist with stripe order. This is also supported by the fact that there is no significant anomaly in SDW and CDW orders at T_c in this material.

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