Magnetic field dependence of charge stripe order in La$_{2-x}$Ba$_x$CuO$_4$ ($x \approx 1/8$)

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We have carried out a detailed investigation of the magnetic field dependence of charge ordering in La$_{2-x}$Ba$_x$CuO$_4$ ($x \approx 1/8$) utilizing high-resolution x-ray scattering. We find that the charge order correlation length increases as the magnetic field greater than $\sim 5$ T is applied in the superconducting phase ($T=2$ K). The observed unusual field dependence of the charge order correlation length suggests that the static charge stripe order competes with the superconducting ground state in this sample.

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Charge inhomogeneity in strongly correlated electron systems such as the cuprate superconductors has drawn much attention for its intimate relationship with exotic charge transport properties. In particular, neutron scattering experiments have revealed that doped holes arrange themselves in orderly rows in the copper oxide plane in certain high-temperature superconductors. This static ordering of charge stripes and associated spin stripes was observed in La$_{1.6-x}$Nd$_x$Sr$_{2}$CuO$_4$ (LNSCO) crystals$^{3,4,5,6}$ More recently, stripe ordering has been investigated in detail in La$_{1.875}$(Ba,Sr)$_{0.125}$CuO$_4$. In other materials, such stripes may also exist, although in most cases the stripes are not static and fluctuate with time and position$^{12,13}$ Understanding the role of stripe physics in cuprate superconductors is believed to be essential in elucidating the superconducting mechanism of the cuprates.

Despite the fundamental importance of charge ordering in the cuprates, only a limited number of experiments have been carried out to study charge stripes$^{8,11,14,15,16}$ and a comprehensive examination of the relationship between charge stripes and superconductivity is still lacking. We note that there have been extensive neutron scattering studies on spin stripe correlations, including measurements of their temperature and magnetic field dependence$^{6,17,18,19}$ while scanning tunneling spectroscopy experiments have shown intricate real space images of checker-board type charge distribution in a number of cuprate superconductors$^{20,21}$ However, no systematic field dependence study of charge ordering has been carried out to date.

We have carried out a detailed investigation of magnetic field dependence of charge order (CO) in La$_{2-x}$Ba$_x$CuO$_4$ ($x \approx 1/8$) (LBCO) utilizing high-resolution x-ray scattering. We find that the correlation length of the charge order exhibits unusual magnetic field dependence. Specifically, the correlation length increases as the magnetic field greater than $\sim 5$ T is applied in the superconducting phase ($T=2$ K). The fact that the CO correlation length grows under the field indicates that the CO correlation length at zero field is not limited by extrinsic factors such as disorders and defects, but is determined by microscopic origin, such as competing ground states. We discuss the implication of the observed field dependence of the CO correlation length to the spatial distribution of CO and SC regions.

The magnetic field dependence study was carried out at the X21 beamline at the National Synchrotron Light Source (NSLS) at Brookhaven National Laboratory. The beamline is equipped with a superconducting magnet that can provide a magnetic field of up to $\mu_0H=10$ T and temperatures as low as $T=2$ K. The incoming photon with energy 15 keV was selected by a double bounce Si(111) monochromator, and horizontal scattering geometry was used. In order to reduce the background and to improve the resolution, a LiF(200) analyzer crystal was placed in the scattering geometry after the sample. The LBCO sample used in our measurements was grown by the traveling-solvent floating zone technique at Brookhaven National Laboratory. The bulk superconducting onset, $T_c$, of the particular sample studied here was measured to be approximately 6 K from magnetic susceptibility.

Fig. 1 shows a schematic (H,K,L) (L=half-integer) plane of the reciprocal space of LBCO. Filled circles (blue) represent the points where Bragg peaks are found in the low temperature orthorhombic (LTO) phase, and filled squares (red) are the points where additional Bragg reflections occur in the low temperature tetragonal (LTT) phase below 55 K. Large open circles (green) represent the (H,K) positions of the incommensurate superlattice peaks arising from the static CO. Note that these CO peaks occur at the half-integer $L$ values, reflecting the criss-crossing pattern of the stripes. Detailed investigation of the magnetic field ($\mu_0H$) dependence was carried out near the (3,7,1,0.5).

The sample was cooled in zero-field to 2 K, which is well below the superconducting and the CO temperature of $\sim 6$ K and $\sim 42$ K, respectively. The magnetic field was applied perpendicular to the CuO$_2$ plane, which coincides with the scattering plane within 2 degrees. The representative scans along the H and K direc-
FIG. 2: (Color online) (a) and (c) show H and K scans, respectively, of the (4 1 0) Bragg peak for $\mu_0 H = 0$ T and 10 T at $T = 2$ K. The dotted lines are Gaussian fits to the raw data. (b) and (d) show H and K scans, respectively, of the (3.77, 1, 0.5) superlattice peak for $\mu_0 H = 0$ T and 10 T at $T = 2$ K. The solid lines in (b) and (d) are fits to a Lorentzian function convoluted with the instrumental resolution which is shown as a dotted line. One can clearly see the sharpening of the peak in both the H and K directions under applied magnetic field.

To see how the intrinsic peak width of the (3.77,1,0.5) peak for two magnetic field values of $\mu_0 H = 0$ T and 10 T at $T = 2$ K are shown in Figs. 2(b) and (d), respectively. The statistical error bars are much smaller than the symbol size in the figure. To facilitate easy comparison of the width change, all scans are plotted as a function of relative momentum transfer, $(\Delta H, \Delta K)$, and are normalized to have matching peak heights.

We can see that the CO peak width is not resolution limited, unlike the Bragg peak whose width is limited by the instrumental resolution. In fact, the width of the CO peak is about twice that of the instrumental resolution which is shown as a dotted line in Figs. 2(b) and (d). In particular, one can clearly see the sharpening of the peak in both the H and K directions under applied magnetic field. This change is not very large (between 10 and 20 %), but based on several tests described below, we believe that this effect is clearly larger than experimental uncertainties.

Firstly, in Figs. 2(a) and (c), we show similar H and K scans for the nearby (4, 1, 0) Bragg peak as a comparison. Both the Bragg peak and the CO peak data were obtained with the same experimental conditions in one setting. In contrast to the CO peak widths, the Bragg peak widths in both the H and K directions are found to remain unchanged with applied magnetic field up to 10 T. Secondly, the measurement was repeated three times using different combinations of magnetic fields. The first run measured the CO peak widths at fields of 0 T and 10 T as displayed in Figs. 2(b) and (d), respectively. The second run measured the peak widths at fields of 0 T, 5 T, and 10 T and the third run at fields of 0 T, 6 T, and 8 T. After each run, the sample was warmed above the CO temperature to eliminate the possibility of sample history dependence. All three runs showed the same magnetic field dependence of the CO peak width.

To see how the intrinsic peak width of the (3.77,1,0.5) superlattice reflection changes with magnetic field, the scans shown in Figs. 2(b) and (d) are fitted to a two-dimensional Lorentzian peak convoluted with the instrumental resolution which was obtained by fitting the (4,1,0) Bragg peak to a Gaussian function. The resulting half-width at half maximum (HWHM, $\kappa$) values are summarized in Fig. 3. Filled and open symbols correspond to $\kappa_H$ and $\kappa_K$, respectively. One can immediately notice that the CO correlation is quite isotropic in the copper oxide plane, which is due to the fact that the stripes on neighboring layers run perpendicular to each
Other values of both \( \kappa_H \) and \( \kappa_K \) at \( \mu_0 H = 0 \) T are approximately 0.0043(3) \( A^{-1} \), corresponding to a correlation length of \( \sim 230 \AA \), which is consistent with results reported earlier. With an increase in \( \mu_0 H \), the peak width decreases, which becomes noticeable above \( \mu_0 H = 5 \) T. At 10 T, \( \kappa_H \) (or \( \kappa_K \)) is about 0.0037(2) \( A^{-1} \), corresponding to a correlation length of \( \sim 270 \AA \), which is about 17% larger than the zero-field value. This change in the correlation lengths corresponds to the correlation area growing from about 3500 unit cells at 0 T to nearly 5000 unit cells at 10 T, an expansion of almost 37%.

Our data show that the charge ordering fails to grow into a true long range order, and its correlation length saturates at \( \sim 230 \AA \). Extrinsic mechanisms such as compositional and structural defects can prevent charge ordering from becoming a true long range. However, the observed increase of the CO correlation length under the field clearly indicates that the CO correlation length is not limited by extrinsic factors, but determined by intrinsic reasons based on microscopic physics.

One should also keep in mind that the charge stripe order in this system is accompanied by spin stripe order. That is, in the hole-poor region between the charge stripes, the antiferromagnetic spin order mimics that of \( \text{La}_2\text{CuO}_4 \). This spin stripe order in LBCO actually goes through spin-flip transition when about 6 T of magnetic field within the copper oxide plane is applied. On the other hand, applying magnetic field along the c-direction does not seem to affect the spin stripe order in any significant way. Of course, magnetic field along the c-direction has direct implication with regard to the superconductivity, and indeed it was observed that there is a weak diamagnetism below 40 K at zero field. This temperature at which diamagnetic signal sets in decreases with increasing field, and the weak diamagnetism is completely suppressed around 7 T. This suggests that the observed field dependence of CO could be the field dependence of superconductivity, since the charge order is unlikely to be affected by magnetic field directly.

In this regard, it is interesting to note that the “critical” field of \( \sim 5 \) T corresponds to the field at which the vortex lattice spacing becomes comparable to the CO correlation length. Using the available neutron scattering data for \( \text{La}_{2-x}\text{Sr}_x\text{CuO}_4 \) one can write the vortex lattice spacing as \( a_0 \sim 500/\sqrt{\mu_0 H} \) in Å with \( \mu_0 H \) in T. This empirical relationship is plotted as a dotted line in Fig. 3. One can see that the CO correlation length does not change at small field, but starts to increase when the separation between vortices becomes similar to the CO correlation length. Further theoretical calculation would be required to elucidate microscopic picture of vortices in stripe ordered cuprates.

We note that, in their study of the transport properties of \( \text{La}_{15/8}\text{Ba}_{1/8}\text{CuO}_4 \) (\( T_c = 2.4 \) K), Li and coworkers observed that the in-plane resistivity drops rapidly below about 16 K in zero field, which was interpreted as the onset of two-dimensional (2D) superconducting transition. Above this temperature, the unbinding of thermally excited vortex-antivortex pairs creates phase fluctuations, and the 2D superconductivity is lost. They also observed that this 2D superconducting transition temperature is suppressed with the c-axis magnetic field, and extrapolates to about 4-5 T at zero temperature, which is similar to the “critical field” in our study. Since the in-plane resistivity is an indirect measure of inverse superconducting correlation area, the data in Ref. [26] suggests that the superconducting correlation length actually decreases. It is interesting to note that this behavior of superconducting correlation length is opposite of what is observed for stripe correlation length in our experiment.

An alternative way to describe stripes and superconductivity in LBCO is the competing order picture. In its extreme form, the competing charge and superconducting order will result in microscopic phase separation. Specifically, one can imagine that the charge order and the superconducting order exist in spatially distinct regions of the sample, and competition between these phases drive the subtle change in their respective domain size. This picture of microscopic phase separation was suggested by Uemura et al. based on their muon spin rotation (\( \mu \)SR) study of the Zn substituted cuprates. In their recent \( \mu \)SR investigation of \( \text{La}_{1-x}\text{Eu, Sr}_x\text{CuO}_4 \), Kojima and coworkers proposed that static stripe magnetism occurs in different spatial regions than the superconductivity.

In summary, we have observed that the correlation length of the charge order in the superconducting phase of \( \text{La}_{2-x}\text{Ba}_x\text{CuO}_4 \) (x \( \approx 1/8 \)) increases as the magnetic...
field greater than \( \sim 5 \) T is applied. This "critical" field scale of \( \sim 5 \) T seems to be an important point in the phase diagram. At this point, the vortex lattice spacing becomes comparable to charge stripe correlation length, and the 2D superconductivity is lost due to phase fluctuations. Taken together, our study suggests that static charge order competes with the superconducting ground state in this LBCO sample. Our experiment also demonstrates that the field-dependent x-ray scattering experiment is useful in probing the physics of charge order and superconductivity.

Acknowledgments

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