Searching for Charge Scattering from Stripes in $La_{2-x}Sr_xCuO_4$ and Related Compounds

R. J. Christianson[1], R. L. Leheny[1], R. J. Birgeneau[1], L. B. Lurio[1], A. R. Sandy[1], S. G. J. Mochrie[1], M. Sutton[2], J. F. Pelletier[2]

[1]Center for Materials Science and Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139
[2]Department of Physics, McGill University, Montréal, Québec, H3A 2T8 Canada

Introduction

Recently, we have initiated an effort at the 8-ID beamline to search for incommensurate charge scattering in the superconducting compounds $La_{1.88}Sr_{0.12}CuO_4$ and La_2CuO_{4+y}. In this report, we describe preliminary measurements of the charge order in $La_{1.48}Nd_{0.4}Sr_{0.12}CuO_4$, and discuss prospects for extending these measurements to the high T_c materials.

The search for incommensurate charge order in the high T_c materials stems from the magnetic behavior observed in these systems with neutron scattering. In 1989, our group at MIT, together with collaborators from BNL and Japan [1,2] discovered that the magnetism in superconducting $La_{2-x}Sr_xCuO_4$ is characterized by dynamic, incommensurate magnetic correlations. These fluctuations manifest themselves as four inelastic peaks displaced in reciprocal space symmetrically around the original antiferromagnetic wave vector by a distance ε. In 1995, Tranquada et al. [4] showed that, when $La_{1.88}Sr_{0.12}CuO_4$ is co-doped with neodymium, suppressing the superconducting transition temperature, the incommensurate magnetic peaks become elastic. They also observed additional satellite peaks displaced by 2ε around the structural Bragg position. Detection of the same peaks by Zimmermann et al [5] in an x-ray scattering experiment confirmed that the source of the scattering was from a corresponding charge stripe pattern.

These discoveries led [3] to a picture of segregation of the doped in-plane charges into 'stripes' of charge separating regions of antiferromagnetic ordering. These stripes provide a compromise between the destruction of short-range antiferromagnetic order that results from a uniform charge distribution and the electrostatic energy necessary to phase-separate the charges to maintain antiferromagnetic order. By elucidating the microscopic behavior of the doped in-plane charges, these theories have direct relevance to understanding the origins of high-temperature superconductivity.

Recent neutron scattering results by Lee et al. [6] on La_2CuO_{4+y} and by Kimura et al. [7] on $La_{1.88}Sr_{.12}CuO_4$ show the existence of static incommensurate magnetic ordering in these superconducting samples. The spin density wave ordering is resolution limited (long-range ordered) and its onset temperature corresponds closely to the measured superconducting transition temperatures (42K and 31.5K respectively). This indicates that there may be a link between the superconductivity and the static stripe ordering. In addition, these results suggest that static charge order, such as was observed in the Nd doped samples, may be also present in these compounds.

However, it was not possible for these groups to observe the charge ordering directly with neutron scattering. In order to assemble a complete picture of stripes and their relation to superconductivity, it is necessary to prove directly the existence of the static charge ordering in these systems and characterize its behavior: including the onset temperature and characteristic length scale. The measurements we have begun at 8-ID have precisely this objective. Xray scattering is the natural probe to examine charge structures, since it is sensitive to ordered charge densities and is relatively insensitive to magnetic ordering, making it easy to distinguish the charge stripes from the associated magnetic superstructure. In addition, Xray scattering is capable of discerning ordering on length scales far exceeding the resolution limit of neutron scattering.

Methods and Materials

Due to the comparatively small amount of charge and associated lattice distortion involved in the stripe formation , it is anticipated (and has been shown in the Nd co-doped samples) that the charge superlattice peaks should be on the order of 10^{-8} of the intensity of the associated structural Bragg peak. Thus, detection of these peaks requires a large incident x-ray flux, a low background, and as large a probed sample volume as possible.

In order to increase the probed sample volume, and insure that surface effects do not interfere with measurements, it is desireable to use higher energies than those available with reasonable flux at a bending magnet. We used the 23 keV third harmonic of the undulator at 8-ID with a flux of approximately 10^{11} photons/second off the Pt-coated stripe of the flat Si mirror and diamond monochromator. This gave us a penetration depth in $La_{1.88}Sr_{0.12}CuO_4$ of nearly .1 mm. We cut and polished a $La_{1.48}Nd_{0.4}Sr_{0.12}CuO_4$ sample with this thickness to use in transmission geometry as a preliminary test of the suitability of these experimental conditions for detecting the charge stripes in $La_{1.88}Sr_{0.12}CuO_4$ and La_2CuO_{4+y}.

Results and Discussion

We observed a pair of superlattice peaks displaced symmetrically around (2 2 0.5) in the longitudinal direction [see figure 1] in $La_{1.48}Nd_{0.4}Sr_{0.12}CuO_4$. These peaks are distinctly broader than our resolution, with a correlation length of about 80 Angstroms, and sit on a sloping background much larger than would be expected with our narrow resolution (approximately .0005 rlu full width at half maximum). The peaks disappear above 70K, the temperature of the LTO-LTT transition, in exact agreement with the results of the experiments done at DESY by Zimmermann et al. However, despite the narrow resolution, our measurements still improve upon the signal to background ratio of the previous experiment. This is important because, while the neutron-scattering experiment on the Nd co-doped samples show that the magnetic superlattice peaks are broadened, the corresponding scans on the non-Nd

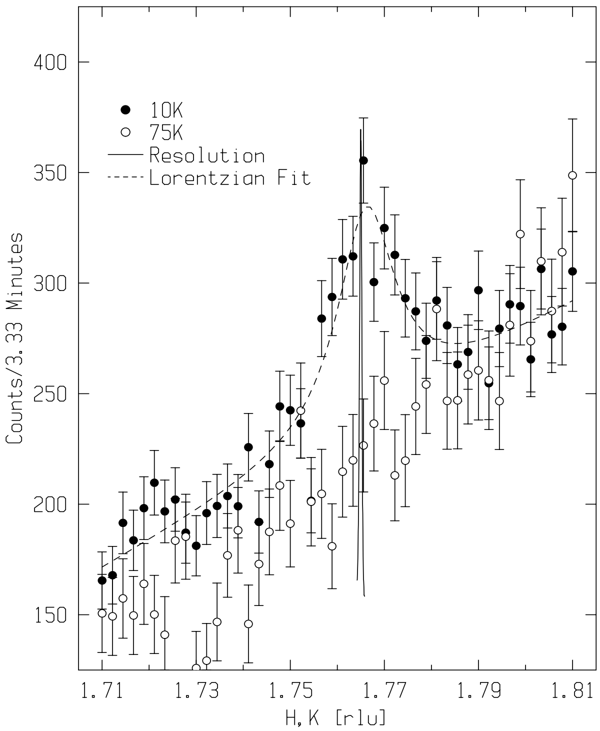

Figure 1: $La_{1.48}Nd_{0.4}Sr_{0.12}CuO_4$ Charge ordering peak at (1.765, 1.765, 0.5) at 10K and 75K. The solid line shows the measured instrumental resolution.

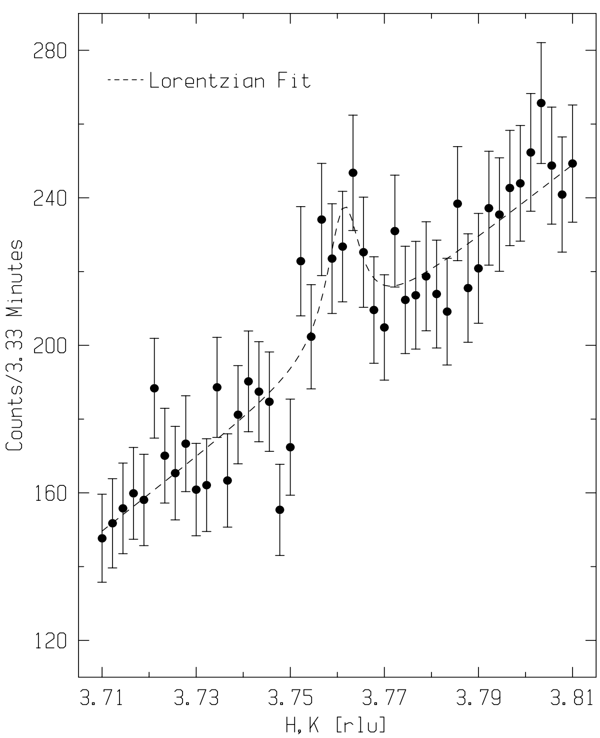

Figure 2: Charge ordering peak at (3.765, 3.765, 0.5) at 10K in $La_{1.48}Nd_{0.4}Sr_{0.12}CuO_4$

doped samples are resolution limited. It may be assumed, therefore, that the associated charge-ordering peaks in $La_{1.88}Sr_{0.12}CuO_4$ may be significantly narrower than in $La_{1.48}Nd_{0.4}Sr_{0.12}CuO_4$. The ability to measure the peaks in $La_{1.48}Nd_{0.4}Sr_{0.12}CuO_4$ with tight resolution may indicate that our current experimental conditions are well suited to measure the narrower peaks we expect to see in $La_{1.88}Sr_{0.12}CuO_4$ and characterize their correlation length.

Extending our search for charge peaks to the (4 4 0) Bragg peak, we observed a peak in the appropriate position on the low-Q side [Figure 2]. This peak was approximately 1/2 the size of the peak at (1.765,1.765,0.5) after accounting for the effects of the beam polarization in the horizontal scattering plane. This ratio provides a useful constraint in understanding the microscopic picture of the stripe structure in this sample. Efforts to find the peak at the low-Q side of the (6 6 0) were not immediately successful.

Acknowledgements

8-ID was developed with support from the NSF Instrumentation for Materials Research Program (DMR 9312543), from the DOE Facilities Initiative Program (DE-FG02-96ER45593), and from NSERC. The APS is supported by the DOE under contract No. W-31-109-Eng-38. We thank Harold Gibson for his invaluable assistance.

References

[1] R.J. Birgeneau et al., Phys. Rev. B 39 (1989) 2868.

[2] T.R. Thurston et al., Phys. Rev. B 40 (1989) 4585.

[3] J. Zaanen et al., Phys. Rev. B. 40 (1989) 7391. V.J. Emery et al., Phys. Rev. Lett. 64 (1990) 475. and references therein.

[4] J.M. Tranquada et al., Nature 375 (1995) 561. J.M. Tranquada et al., Phys. Rev. B 54 (1996) 7489.

[5] M.v. Zimmermann et al., Europhys. Lett. 41, 6 (1998) 629.

[6] Y.S. Lee et al., Phys. Rev. B 60 (1999) 3643.

[7] H. Kimura et al., Phys. Rev. B 59 (1999) 6517.